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PROVISIONAL SPECIFICATION

Invention Title A Method of Weighing Vehicles in Motion and Systems Formed for that Purpose

The invention is described in the following statement:

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A METHOD OF WEIGHING VEHICLES IN MOTION AND SYSTEMS FORMED FOR THAT PURPOSE

FIELD OF THE INVENTION

This invention relates to a method and systems formed for weighing vehicles in motion. The methodology and systems disclosed in this provisional specification offer a radically different approach to the problem of monitoring vehicle weigh-in-motion (WIM) by allowing continuous in-road monitoring, thus revolutionising WIM systems for pavement monitoring and enforcement applications.

The methodologies and systems disclosed in this provisional specification were developed under a four year R&D project supported by the Australian Government Department of AusIndustry, through the Industry Innovation Program Competitive Grants scheme. The title of that project was: "Fibre Optic Weigh-In-Motion Detection in the Infrastructure Field", AusIndustry Project Ref. No. GRA00175. This was a collaborative project involving Future Fibre Technologies Pty. Ltd. (FFT), ARRB Transport Research Ltd. (ARRB) and Remedial Engineering Pty. Ltd. (RE).

The WIM systems disclosed in this provisional specification are unique and offer new technologies and methodologies never before commercially available for WIM. Furthermore, they offer many operational and cost advantages.

ART BACKGROUND

The pressure on existing road systems throughout developed countries is increasing. In particular, the loads which heavy vehicles impose on pavements and bridges have a direct and disproportionate bearing on the rate of wear and the life of the infrastructure and, therefore, on the associated maintenance, refurbishment and replacement costs. Road transport managers require a vehicle data system to provide information that will enable them to manage the road transport network in the most economical and efficient manner. One such piece of required vehicle information is mass. As the demand for better roads has increased and as the emphasis has turned from new construction to actual conservation, there have been considerable technical developments to produce more efficient and accurate vehicle mass collection mechanisms, namely, weigh-in-motion (WIM).

In recent years, government and private industry have been giving considerable attention to the development of practical and effective methods for instrumenting infrastructure in order to monitor traffic conditions, enforce load restrictions and determine the state of health of the infrastructure. Vehicle WIM monitoring systems, capable of automatically and accurately measuring the configuration, speed and weight of moving vehicles, continue to play a major role in this endeavour. However, current WIM techniques in use worldwide possess a number of limitations, which may be overcome by the use of the new installation technique and the novel sensing configurations disclosed in this provisional specification. The potential for the development of higher accuracy, lower cost WIM systems for pavement monitoring and enforcement applications offered by this radically different approach is significant.

The basic principles of WIM technology were developed in the 1950s. However, adequate instrumentation, data processing and storage and suitable weight sensors were non-existent or at best crude. Solid-state electronics and digital computers came into practicable use in the 1960s. Weight sensor development also continued.

Commercial WIM devices currently in use throughout the world include:

1. Plates or beams instrumented with strain gauges, load cells or capacitive strips. [1, 7, 8]
2. Culverts and bridges instrumented with strain gauges. [2, 4, 5, 9, 11]
3. Piezoelectric strips. [3, 6, 10]

All of these methods have one or more disadvantages including varying degrees of accuracy, cost, installation difficulties, and reliability. It is arguable that, to date, no system has been able to reliably and consistently weigh random vehicles at highway speeds to enforcement accuracy (within ±5% of gross vehicle mass, 95% of the time).

In Australia, the late 1960s and early 1970s saw one of the applicants of this provisional specification, ARRB Transport Research Ltd. (ARRB), working on numerous methods of weighing vehicles at low and high speeds. One of the systems consisted of a steel plate supported along two of its edges and mounted flush with the road surface. The system electronically measured the resulting strain produced. [1]

As a production tool, the first WIM system to appear in Australia was the Low Speed Electronic Mass Unit (LSEMU). Developed by ARRB, the LSEMU was a law enforcement device comprising a plate supported by four load cells.

Following extensive ARRB research and experience with LSEMU, the decision was made in 1978 to investigate the application of the system to high speed weighing. This culminated in the High Speed Electronic Mass Unit (HSEMU). [7]

Australia has also pioneered the use of strain gauge weight sensor systems. The Main Roads Department - Western Australia, developed a bridge based strain gauge system called AXWAY. [4] Experience with AXWAY led the Main Roads Department - Western Australia in conjunction with ARRB to develop CULWAY. With CULWAY, strain gauges were mounted onto a culvert rather than a bridge. [5]

To date, ARRB has developed several highly successful vehicle WIM systems capable of measuring the configuration, speed and weight of moving vehicles. These systems play a major role in providing the feedback required to extend the lifetimes of existing road systems and infrastructure. Australian use of WIM can be characterised into a number of uses and applications, as follow:

- infrastructure design and management;
- freight/trade planning and regulation; and
- enforcement and detection.

Like many research organisations throughout the world, ARRB has investigated a number of potential advances and totally new high-speed weight sensor types, as follow:

- concrete culverts - different version of CULWAY;
- strain gauged plates;
- piezoelectric cables;
- hydraulic tubes - consisting of a pneumatic tube filled with an incompressible fluid and embedded in a rubber pad; and
- capacitive strips.

These new weight sensors have demonstrated promising results in the laboratory. However, during actual field tests, the results have not been satisfactory.

Consequently, since 1995, ARRB has been researching and investigating the use of leading-edge fibre optic sensing technology for detecting and weighing moving vehicles with the other applicant of this provisional specification, Future Fibre technologies Pty. Ltd. (FFT).

Engineered structures are usually not monitored in real-time due to the difficulties in connecting conventional sensors to them and because of the limitations of the sensors. This is particularly so when dealing with pavements. In the case of detecting and measuring moving vehicle weights on roads, an accurate, cost-effective and in-road sensing system is not readily available; commercially available equipment suffers from a number of limiting problems. Either temporary, surface mounted sensors on roads or instrumented culverts are used to perform a reasonably accurate, but non-enforceable, estimate of vehicle weights. Accurate, enforcement quality (within 5%) measurements are generally limited to low-speed or stationary measurements at specially made and relatively costly static weigh stations. Furthermore, with conventional weigh stations, drivers are inconvenienced and station staff spend most of their time checking the vast majority of vehicles that conform, thus it is a very time consuming and costly exercise. The combination of the HSEMU and LSEMU, developed by ARRB, overcomes some of these problems. The HSEMU, which measures the weight of vehicles travelling at highway speeds, but to a non-enforceable accuracy, provides an initial screening, so that only non-conforming vehicles proceed to the enforcement accuracy LSEMU. On the other hand, a load sensor incorporated within the road itself which continuously and accurately monitors moving vehicle weights in real-time should provide significant cost, time and asset savings. To date, however, effective, enforcement quality, real-time weigh-in-motion systems that can be embedded in the roads are not commercially available.

Fibre optic sensors offer a radically different approach to this problem and could allow continuous, in-road WIM monitoring, thus revolutionising WIM systems for pavement monitoring and enforcement applications. This is possible because optical fibres can be more than mere signal carriers. Light that is launched into and confined to the fibre core propagates along the length of the fibre unperturbed unless acted upon by an external influence. Specialised sensing instrumentation may be configured such that any disturbance of the fibre which alters some of the characteristics of the guided light (ie., amplitude, phase, wavelength, polarisation, modal distribution and time-of-flight) can be monitored, and related to the magnitude of the disturbing influence. Such modulation of the light makes possible the measurement of a wide range of events and conditions, including:

- Strain
- displacement
- vibration/frequency
- acoustic emission
- temperature
- load

Fibre optic sensor technology has progressed at a rapid pace over the last decade. Different configurations of fibre sensing devices have been developed for monitoring specific parameters, each differing by the principle of light modulation. [16] Fibre optic sensors may be intrinsic or extrinsic, depending on whether the fibre is the sensing element or the information carrier, respectively. They are designated "point" sensors when the sensing gauge length is localised to discrete regions. If the sensor is capable of sensing a measurand field continuously over its entire length, it is known as a "distributed" sensor; "quasi-distributed" sensors utilise point sensors at various locations along the fibre length. Fibre optic sensors can be transmissive or can be used in a reflective configuration by mirroring the fibre end-face.

Hence, fibre optic sensors are actually a class of sensing device. They are not limited to a single configuration and operation unlike many conventional sensors such as electrical strain gauges and

piezoelectric transducers. Consequently, fibres are now replacing the role of conventional electrical devices in sensing applications to the extent where we are now seeing a multitude of sensing techniques and applications being explored for practical gain.

The advantages of fibre optic technology for WIM applications lie in its speed, security, safety, sensitivity and robustness, as well as its immunity to corrosion and electromagnetic interference. Additionally, these devices provide several operational advantages for WIM systems over existing technologies, such as in-situ (embedded in the pavement) sensing, real-time measurement, on-line analysis, simultaneous, distributed sampling, component miniaturisation and opportunity for feedback control.

Consequently, fibre optic sensors potentially offer the WIM industry lower cost products with enhanced capabilities. Installing the sensors directly into the pavement offers the ability to reduce vehicle-to-sensor, impact-related sensor response inconsistencies, and will result in significant installation and infrastructure cost savings and the potential for automated enforcement techniques. Consequently, the decreasing cost, inherent properties and operational advantages of fibre optic sensing technologies are anticipated to significantly reduce the cost and complexity of future WIM monitoring systems.

As a result, considerable research has been underway over the past decade into the development of fibre optic WIM systems. Previous research in this area involved the use of the following fibre optic sensing techniques:

1. Modalmetric multimode and microbending techniques: [17, 19-23, 25, 29, 32]

   Although this type of sensor is very sensitive, the modulation of the modal pattern is generally non-linearly related to all disturbances, resulting in deep fading and drifting of the output signal. This behaviour limits the use of this sensor for quantitative strain measurements, but nonetheless it can be used as a threshold-type sensor. Modalmetric sensors are capable of sensing many parameters, however, their sensitivities are generally lower than interferometric sensors and localisation of the sensing region is difficult (resulting in sensitive leads). However, for WIM applications the modalmetric sensors offer the advantage of detecting disturbances over long lengths of fibre (they are generally a distributed sensor).

   A major problem experienced with the prior art results using this sensor to date is that almost all the work has been based on a surface-mounted pad or elevated platform, creating significant impact-related sensor response inconsistencies or requiring the vehicle to approach at a very low speed. None of the prior art techniques used sensors embedded in the road.

2. Interferometric techniques: [28]

   Interferometric fibre optic sensors are a large class of extremely sensitive fibre optic sensors. Fibre optic interferometers are analogous to their respective classic bulk optic interferometers. Fibre optic interferometers are generally intrinsic sensors in which light from a coherent source is equally divided to follow two (or more) fibre-guided paths. The beams are then recombined to mix coherently and form a "fringe pattern" which is directly related to the optical phase difference experienced between the different optical beams. This sensing technique is based primarily on detecting the optical phase change induced in the radiation field as it propagates along the optical fibre.

   They are typically used when ultra-high sensitivities are required and/or in applications of localised measurements (ie., point sensing), although sensor lengths longer than one metre are sometimes possible. Singlemode fibre and associated components are used because they maintain the required spatial coherence of the light beam, whereas multimode fibres do not. The ultimate sensitivity and resolution of interferometers are limited by the effectiveness of the phase demodulation signal processing techniques used to interrogate the sensors. Although this class of sensor offers very high sensitivity, it has been largely restricted to point

sensing, due to the requirement for a long coherence length light source, thereby limiting its usefulness for WIM applications.

3. Polarimetric techniques: [18, 24, 26, 27]

   Polarimetric fibre optic sensors are an attractive alternative to interferometric sensors when ultra-high sensitivity is not required, and longer sensor gauge lengths are desired. The polarimetric fibre optic sensor is capable of detecting many parameters with the advantage of being configured as a point sensor or distributed. Significant drawbacks of this sensor include the high cost of components and the complexity of the system (polarisation control, maintaining and monitoring components are required). The development of an accurate and reliable polarimetric system is further complicated by an inherent large sensitivity to temperature compared to strain (~40:1).

   A major problem with the prior art results using this sensor to date is that almost all the work has been based on a surface-mounted pad or platform, creating significant impact-related sensor response inconsistencies or requiring the vehicle to approach at a very low speed. None of the prior art techniques used sensors embedded in the road.

4. Linear Modalmetric Interferometer: [30, 31]

   In the first two years of their collaborative R&D project, the applicants of this provisional specification experimented with the use of a novel linear modalmetric interferometer [33] inserted into saw-cuts on the surface of pavements. This sensing technique is based on the modulation of the modal distribution (effectively changing the intensity) in a multimode optical fibre by external disturbances. This technique overcomes the inherent weaknesses of most multimode fibre optic sensors, offering truly localised, mechanically stable and linear sensing. In this method, the sensor response is a direct function of the disturbance on the sensitised portion of the fibre, regardless of where the disturbance occurs along the length. The disturbance may be in the form of physical movement (ie., compression (radially or axially), elongation, twisting, vibration, etc.) or microphonic effects (ie., travelling stress waves or acoustic emissions). This sensor had a further advantage over other modalmetric sensors in that it can operate as a single-ended device by mirroring the fibre end-face. Unfortunately, this sensor and the surface saw-cut installation technique were found to suffer from various problems, rendering it unsuitable.

   However, the applicants continued to research this sensor for its suitability as an axle detector and obtained promising results. This work has not yet been published.

Owing to the inherent problems and inconsistencies reported and experienced with the above-detailed techniques, the applicants of this provisional specification did not consider any of these to be practical for WIM applications. This observation is particularly justified when considering that research in this field has been underway for more than ten years and there is not yet a commercially available product.

Consequently, the applicants of this provisional specification investigated and developed completely new methods of installing the WIM sensing devices and new configurations of fibre optic sensors. The outcomes of this work are contained and claimed in this provisional specification.

The main innovative features contained in the inventions disclosed in this provisional specification are:

- Installation of the WIM sensing devices is performed by boring horizontally under the pavement at a typical depth of 500 to 1,000 mm below the surface, which is usually into the

sub-grade material of the road. The axle detecting devices may also be installed in the same borehole. Therefore, the pavement itself acts as the weighing device.

- The systems operate using conventional electrical strain gauges or other advanced sensing devices, such as fibre optic sensors. One strain gauged configuration and two new fibre optic sensing configurations are disclosed in this provisional application.
- The WIM sensing devices are instrumented in a simple extrusion configuration in the factory, which enables easy handling and transportation for installation.
- The axle detecting devices may be surface mounted on the pavement or instrumented in the same borehole extrusion as the WIM sensing devices.
- The WIM systems are microprocessor based and fully automated, providing real-time data logging and analysis features, and can be monitored and controlled locally or remotely.

Over the course of the four-year R&D project, FFT and ARRB refined and perfected the procedure for the below-pavement borehole installation method. This is an important and exciting aspect of the invention for the following reasons:

- Infrastructure costs are low – no culverts, bridges or weigh stations are required since the road itself becomes the weighing device. Therefore, a system can be installed virtually anywhere in a road network.
- The pavement does not need to be cut from the surface - installation is accomplished by boring in from the side of the road. In this sense, it is considered non-intrusive, unlike culverts, bridges, plates and strips.
- Traffic does not need to be stopped or detoured during installation, reducing installation costs and increasing safety - a major advantage.
- The system is not visible and the road surface is unaffected, thus the system is virtually unnoticeable and less likely to be evaded. Furthermore, the road can be resurfaced without the risk of damaging the sensing devices.
- The system operates at low and high (highway) speeds.
- Temperature effects and other variations are minimised at the pavement depth of operation.
- Calibration is performed in a similar manner as existing technologies.

ARRB is a respected supplier of high quality, survey grade systems to the industry. The extension of the WIM product range with a flexibly-sited, enforcement quality WIM system based on the inventions disclosed in this provisional application would open a new market segment with worldwide application and commercialisation potential. Many road authorities are seeking this type of equipment by trialing existing technologies, however, the very high accuracy and reliability demanded at highway speeds for enforcement, and the need for ease of installation, have thwarted these attempts. Market research, to date, indicates that the method and systems disclosed in this provisional specification offer the world's first practical, commercially viable, enforcement quality fibre optic WIM systems.

Direct discussions with the industry have verified that there is very good commercial potential for the disclosed inventions, if the systems are cost effective, easy to install, do not require a culvert, do not require road closures, are at least as accurate as CULWAY, have low power consumption, are easy to use and invisible to road users. This is a lot to ask for in a WIM system, but achievable with the inventions disclosed in this provisional specification.

It is important to note that the technology is considered to have good potential over competing techniques particularly because of the simplicity of sensor installation into the pavement, the excellent potential for system automation (ie., using cameras and remote communications) and reduction in the required installation and operational infrastructure costs.

Conventional WIM systems cost between $20,000 and $200,000. The cost of a fully installed conventional WIM system can be considerably more (between $40,000 to over $1 million) due to the large installation costs involved (ie., requirement for culverts or construction of highway bypass weigh stations, etc.).

Indicative prices of a future WIM system based on the inventions disclosed in this provisional specification are between $500 and $2,000 per load sensing device and between $20,000 and $60,000 for the instrumentation (depending on the number of lanes and channels being monitored). Most significantly, though, the large installation and infrastructure costs of constructing and instrumenting culverts and bypass weigh stations will be reduced dramatically since the sensors are simply installed into a borehole under the pavement. Therefore, monitoring of vehicle WIM could be performed on any road in virtually any location, without significant downtimes or costs associated with the system installation, as well as the possibility of not having to stop the vehicles to perform the weighing.

Therefore, the inventions disclosed in this provisional specification potentially offer lower cost products with enhanced capabilities. The decreasing cost, inherent properties and operational advantages of fibre optic sensing technologies are anticipated to significantly reduce the cost and complexity of future WIM systems.

REFERENCES CITED

1. Tritt, B.H., "ARRB Research Into Methods of Weighing Vehicles", *Australian Road Research Board Internal Report AIR 121-1*, 1976.
2. Moses, F., "Weigh-in-Motion System Using Instrumented Bridges", *Transportation Engineering Journal of ASCE, Proceedings of the American Society of Civil Engineers*, Vol. 105, No. TE3, pp. 233-249, 1979.
3. Robert, R.C., "Detector for Detecting the Passage of Heavy Objects on a Roadway", USA Patent No. 4,383,239, 10 May, 1983.
4. Peters, R.J., "AXWAY – A System to Obtain Vehicle Axle Weights", *Proceedings of the 12th ARRB Conference, Australian Road Research Board 12/1*, 1984.
5. Peters, R.J., "CULWAY – An Unmanned and Undetectable Highway Speed Vehicle Weighing System", *Proceedings of the 13th ARRB Conference, Australian Road Research Board 13/6*, 1986.
6. Siffert, M., Briant, G., Feunten, P., Goacolou, H., Petitgrand, J.C. and Peyret, F., "Process and Apparatus for Measuring the Dynamic Loads Applied to a Highway by the Road Traffic", USA Patent No. 4,712,423, 15 December, 1987.
7. Samuels, S.E., "Development and Evaluation of Highway Speed Weigh-In-Motion Systems in Australia", *Australian Road Research Board Special Report 40*, 1988.
8. Loshbough, R.C. and Hall, D.L., "Vehicle Weighing in Motion Apparatus and Method", USA Patent No. 5,002,141, 26 March, 1991.
9. Snyder, R.E., Moses, F., Burke, B.E. and Kennedy, D.A., "Bridge Weigh-in-Motion", USA Patent No. 5,111,897, 12 May, 1992.
10. Violette, E. and Fillastre, D., "Un Nouveau Barreau de Pasage Renforce de Fibre de Verre", *Proceedings: First European Conference on Weigh-in-Motion of Road Vehicles*, Zurich, Switzerland, pp. 355-360, March, 1995.
11. Znidaric, A. and Baumgartner, W., "Bridge Weigh-in-Motion Systems – an Overview", Pre-Proceedings 2nd European Conference on Weigh-in-Motion of Road Vehicles, pp.139-151, September, 1998.

12. Rouse, G.F and Volna, W.M., "Magnetometer Vehicle Detector", USA Patent No. 5,491,475, 13 February, 1996.

13. Taylor, B. and Bergan, T., "Sensor Array System for Determining Axle Spacing", USA Patent No. 5,621,195, 15 April, 1997.

14. Buisson, C., Fillastre, D. and Violette, E., "Process for Conditioning and for Placing a Traffic Sensor", USA Patent No. 5,520,056, 28 May, 1996.

15. Turk, F.J., Cybulski, C.E. and Hoekman, E.B., "Apparatus for Sensing Vehicles", USA Patent No. 5,850,192, 15 December, 1998.

16. Measures, R.M., "Smart Structures with Nerves of Glass", *Reviews of Progress in Aerospace Science*, Vol. 26, pp. 289-351, 1989.

17. Ibanez, P., Stoessel, J. and Barrett, D.C., "Method and Apparatus for Measuring the Weight of a Vehicle While the Vehicle is in Motion", USA Patent No. 4,560,016, 24 December, 1985.

18. Tardy, A., Jurczyszyn, M., Caussignac, J.M., Morel, G. and Briant, G., "High Sensitivity Transducer for Optical Fibre Pressure Sensing Applied to Dynamic Mechanical Testing and Vehicle Detection on Roads", Springers Proceedings in Physics: Optical Fiber Sensors, Vol. 44, Springer Verlag, Berlin, pp. 215-221, 1989.

19. Ahmed, S.U. and Jones, G.R., "Optical Fibre Axle Sensors", *UK Transport and Road Research Laboratory Contractor Report 217*, Dept. of Transport, UK, pp. 1-47, 1990.

20. Stevens, A., Spindlow, J.R. and Jones, G.R., "Fibre-Optic Axle Sensors for Vehicle Data Collection", Proceedings of the 3rd International Conference of Institution of Electrical Engineers on Road Traffic Control, London, pp. 148-152, 1990.

21. Muhs, J.D., Jordan, J.K., Scudiere, M.B. and Tobin, K.W., "Results of a Portable Fiber-Optic Weigh-in-Motion System", *Proceedings: SPIE Fiber Optic and Laser Sensors IX*, Vol. 1584, pp. 374-386, 1991.

22. Quinlan, T.J., "Fiber Optic Load Sensing Device", USA Patent No. 5,056,884, 15 October, 1991.

23. Ahmed, S., Jones, G.R., Spindlow, J.R. and Stevens, A., "Intrinsic Optical Fibre Sensors for Axle Detection", *Traffic Engineering + Control*, pp. 527-530, November, 1991.

24. Teral, S., "Vehicle Weighing in Motion with Fiber Optic sensors", Proceedings: SPIE 1st European Conference on Smart Structures and Materials, Glasgow, UK, pp. 139-142, 1992.

25. Muhs, J.D., Jordan, J.K., Tobin, K.W. and LaForge, J.V., "Apparatus for Weighing and Identifying Characteristics of a Moving Vehicle", USA Patents No. 5,260,520, 9 November, 1993.

26. Boby, J., Teral, S., Caussignac, J.M. and Siffert, M., "Weighing of Vehicles in Motion Using Fiber Optic Sensors", *Electrical Communication*, pp.74-77, 1st Quarter, 1994.

27. Teral, S., Caussignac, J.M. and Siffert, M., "Vehicle Weigh-in-Motion With Fibre Optic Sensors", *Proceedings: First European Conference on Weigh-in-Motion of Road Vehicles*, Zurich, Switzerland, pp. 333-340, March, 1995.

28. Navarrete, M.C. and Bernabeu, E., "WIM Sensors Based on a Fibre Optic Interferometer", *Proceedings: First European Conference on Weigh-in-Motion of Road Vehicles*, Zurich, Switzerland, pp. 349-353, March, 1995.

29. Cosentino, P.J., Grossman, B.G., Tongta, R., Taylor, C.L., Christenson, J. and Eckroth, W.V., "Microbend Fiber-Optic Traffic Sensor", *Proceedings National Traffic Data Acquisition Conference*, Albuquerque, New Mexico, May, 1996.

30. Buckmaster, R. and Tapanes, E.E., "Australian Developments in Fibre Optic Weigh-In-Motion", *Proceedings: ARRB Weigh-in-Motion Symposium*, Melbourne, Australia, May, 1996.

31. Buckmaster, R., Tapanes, E.E., Goode, J.R. and Cropley, S., "Field Trials of a Fibre Optic Sensor Embedded in Pavements for Vehicle Weigh-In-Motion", *5th International Symposium on Heavy Vehicle Weights and Dimensions*, Maroochydore, Australia, 29 March - 2 April, 1998.

32. Grossman, B.G., "Flexible Optical Fiber Sensor Tapes, Systems and Methods", USA Patent No. 5,913,245, 15 June, 1999.

33. Tapanes, E., "Optical Sensors and Method for Producing Fibre Optic Modalmetric Sensors", Patents Convention Treaty International Patent No. PCT/AU95/00568, 13 September, 1994.

34. Koo, K.P., Tventen, A.B. and Dandridge, A., "Passive Stabilization Scheme for Fiber Interferometers Using (3 x 3) Fiber Directional Couplers", *Applied Physics Letter*, Vol. 41, No. 7, pp. 616-618, 1982.

35. Sheem, S.K., Giallorenzi, T.G. and Koo, K., "Optical Techniques to Solve the Signal Fading Problem in Fiber Interferometers", *Applied Optics*, Vol. 21, No. 4, pp. 689-693, 1982.

36. Kersey, A.D., Jackson, D.A. and Corke, M. , "Suitable for Use in the Single-Mode Fibre Interferometer", *Electronics Letters*, Vol. 18, No. 9, pp. 392-393, 1982.

37. Koo, K.P., Bucholtz, F. and Dandridge, A., "Passive Stabilization of a Fiber-Optic Nonlinear Sensor by Using a Sampling Scheme", *Optics Letters*, Vol. 12, No. 6, pp. 440-442, 1987.

38. Huang, S.Y., Park, H.G. and Kim, B.Y., "Passive Quadrature Phase Detector for Coherent Fiber Optic Systems", Optical Fiber Sensors, Springer Proceedings in Physics, Vol. 44, Springer-Verlag, Berlin, Germany, pp. 38-43, 1989.

39. Koo, K.P., Dandridge, A. and Tventen, A.B., "Performance Characteristics of a Passively Stabilized Fibre Interferometer Using a (3 x 3) Fiber Directional Coupler", *Proceedings Optical Fibre Sensors Conference*, London, England, pp. 200-204, April, 1983.

40. Stephens T.D. and Nicholson, G., "Optical Homodyne Receiver - With a Six – Port Fibre Coupler", *Electronics Letters*, Vol. 23, No. 21, pp. 1106-1107, 1987.

41. Pietzsch, J., "Scattering Matrix Analysis of (3 x 3) Fiber Couplers", *Journal Of Lightwave Technology*, Vol. 7, No. 2, pp. 303-307, 1989.

42. Trommer, G. "Wavelength Dependence Of (3 x 3) Fibre Couplers For Gyro Applications", *Electronics Letters*, Vol. 25, No. 15, pp. 944-945, 1989.

43. Valis, T., Tapanes, E. and Measures, R.M., "Passive Quadrature Demodulated Localized Michelson Fiber Optic Strain Sensor Embedded in Composite Materials", *IEEE Journal of Light Wave Technology*, Vol. 9, No. 4, pp. 535-544, April, 1991.

44. Kwon, I.B., Kim, C.G. and Hong, C.S., "A Digital Signal Processing Algorithm for Structural Strain Measurement by a 3x3 Passive Demodulated Fiber Optic Interferometric Sensor", *Journal of Smart Materials and Structures*, Vol. 8, pp.433-440, 1999.

45. Travis, A.R.L. and Carroll, J.E. , "Possible Fused Fibre In-Phase/Quadrature Measuring Multiport", *Electronics Letters*, Vol. 21, No. 21, pp. 954-955, 1985.

46. Niemeier, Th. and Ulrich, R., "Quadrature Outputs From Fiber Interferometer With (4 x 4) Coupler", *Optics Letters*, Vol. 11, No. 10, pp. 677-679, 1986.

47. Xiaopin, Z., Liping, S. and Peida, Y., "New Structure Of Optical Homodyne Receiver Utilising a (4 x 4) Fibre Directional Coupler", *Electronics Letters*, Vol. 24, No. 19., pp. 1212-1213, 1988.

48. Mortimore, D.B., "Monolithic (4 x 4) Single-Moded Fused Coupler", *Electronics Letters*, Vol. 25, No. 10, pp. 682-683, 1989.

49. Mortimore, D.B., "Theory and Fabrication of (4 x 4) Single-Mode Fused Optical Fiber Couplers", *Applied Optics*, Vol. 29, No. 3, pp. 371-374, 1990.

BRIEF SUMMARY OF THE INVENTION

The object of the present invention is to provide a method and systems formed for weighing vehicles in motion. The method comprising the following key elements:

- A load sensing device specially configured in the form of a sensing extrusion instrumented with a multiplicity of conventional electrical strain gauges or a suitable number of other advanced sensing devices, such as fibre optic sensors, as the strain/load sensing units;
- Installation of the load sensing device, which operates across a partial or an entire lane of interest, in a borehole relatively deep under the pavement surface. Therefore, the pavement itself acts as the weighing device;

- Installation of an axle detecting device, which operates across an entire lane of interest, either surface mounted on the pavement or instrumented in the same borehole extrusion as the load sensing device; and
- Instrumentation capable of real-time data logging and analysis of the signals from the load sensing and axle detecting devices and displaying and/or transmitting the information in a suitable manner.

The objects, advantages and other features of the present invention will become more apparent upon reading of the following non-restricted descriptions of preferred embodiments thereof, given for the purpose of examplification only with reference to the accompanying drawings.

The preferred embodiment of the present invention provides a method and systems formed for weighing vehicles in motion as the wheels of the vehicle pass over the location of the sensing device(s) embedded deeply below the pavement, which may comprise the steps of:

- providing a load measuring device configured in a suitable extrusion utilising a multiplicity of electrical strain gauges or a multiplicity of point fibre optic sensors or single distributed fibre optic sensors which respond to the load applied by the vehicle wheels as it passes over the location of the device and displaces the pavement;
- providing a load measuring device installed in a borehole and at a suitable depth under the pavement surface and operating along the entire length of the device so as to cover the lane of interest;
- optionally providing more than one instrumented borehole along the same wheel path as the first borehole in order to have more than one weight measurement to average and possibly to provide additional information about the vehicle, such as speed, vehicle classification, axle spacings, number of tyres per axle, lane position, etc.;
- providing a suitable number of axle detectors mounted on the surface of the pavement as closely co-directional and co-located with each of the instrumented boreholes as possible or mounted in each borehole load measuring extrusion in order to provide certain information about the event, such as vehicle number of axles, speed, vehicle classification, axle spacings, number of tyres per axle, lane position, etc.;
- providing instrumentation associated with the load sensing device having output signals associated with the magnitude of load or displacement detected by the load sensing device;
- providing instrumentation associated with the axle detectors having output signals associated with the occurrence and timing of the vehicle wheel passing over the axle detector locations;
- providing automated system instrumentation which accepts the information from the load sensing device and axle detector instrumentation and suitably analyses, records, displays and transmits the information;
- calibrating the installed load sensing device by a suitable industry recommended process involving passing a vehicle or a number of vehicles of known weight a number of times across the sensing device location, varying the vehicle weight and speed, to establish a statistically derived calibration factor for the WIM site;
- optionally, if a number of load sensing devices are used at a WIM site then the system is calibrated as described above by a suitable average or weighted average of the responses from the load sensing devices;
- providing the site calibration factor to the system instrumentation in order to maintain the system weight measurements within the required level of accuracy;

- acquiring the output signals of the various devices in the system as a vehicle passes by the WIM site;
- analysing the signal characteristics using suitable algorithms, taking into account the site calibration factor, so as to determine the weight and any other desired information (ie., speed, classification, etc.) for the vehicle; and
- recording the vehicle information in a system database and displaying or transmitting the vehicle information locally and/or remotely.

The preferred embodiment of the present invention provides a method for installing a WIM load sensing device, and possibly axle detectors, in a borehole deeply below the pavement, which may comprise the steps of:

- producing a suitable diameter, horizontal borehole across the pavement lane(s) of interest using any suitable boring techniques;
- inserting the specially configured, instrumented extrusion into the borehole to the desired location;
- filling the remaining borehole void with an epoxy filler, or any other suitable filler material;
- protecting the sensor leads in a suitable manner, possibly running them in conduits to the WIM system instrument; and
- restoring site of borehole entry to its original form, rendering the site invisible to vehicle operators.

The preferred embodiment of the present invention incorporates a data logger in the system instrumentation, which consists of several opto-electronic and/or electronic cards housed in an enclosure. Several WIM sensor inputs can be provided, as well as axle detector inputs. The data logger matches up axle detections with strains produced by an axle travelling over the WIM sensor(s) and stores this information, along with the date/time, into the data logger's internal memory. The information is also available in real-time to allow the system to be used as part of a screening or enforcement system. In a preferred embodiment of the invention, a modem is connected to the system to provide remote data downloading or monitoring capability. The WIM system software allows local or remote monitoring of vehicles travelling over the WIM sensors. For each vehicle, typical parameters displayed are:

- vehicle classification
- axle/wheel configuration
- vehicle speed
- axle group masses
- gross vehicle mass

In addition, many violation checks can be performed on each vehicle, including:

- axle mass overload
- axle group mass overload
- gross vehicle mass overload
- bridge formulae conformance
- 'pig' trailer dimensional conformance
- avoidance

In a preferred embodiment, but without limitation, the instrumented extrusion is made from a PVC plastic U-channel. The electrical strain gauges or fibre optic sensors are suitably attached to the inner flat surface of the PVC U-channel and the extrusion is then preferably filled with the same epoxy used to fill the borehole or any other suitable filler material. The instrumented and packaged extrusion is then ready to be inserted into the borehole. In other preferred embodiments, the extrusion with electrical strain gauges is not filled with the epoxy.

In another preferred embodiment, the extrusion comprises a flat metallic beam inserted into a PVC conduit. The electrical strain gauges or fibre optic sensors are suitably attached to a flat surface of the flat metallic beam. The instrumented beam is then inserted inside a PVC conduit and suitably fastened to the conduit. The conduit is then capped or sealed on both ends to prevent moisture ingress, with the sensor leads exiting though a suitable gland at one end of the conduit. The instrumented and packaged extrusion is then ready to be inserted into the borehole.

In other embodiments of the invention the extrusions are made from other suitable materials.

In a preferred embodiment of the invention, but without limitation, the boreholes are filled with a suitable epoxy filler to fill all voids. In other embodiments, any other suitable filler material may be used. In yet other embodiments, little or no filler may be used.

In a preferred embodiment of the invention, but without limitation, the borehole is produced such that it is horizontal across the pavement and at a perpendicular direction to the traffic flow. However, in other embodiments the borehole may be used at any other desired angles.

In a preferred embodiment of the invention, but without limitation, more than one instrumented borehole may be used along the same wheel path, usually parallel to one another and spaced between 5 to 10 metres apart. Using multiple sensors should assist to decrease the measurement error by averaging-out wind, speed and rough pavement effects on vehicle suspensions, as well as enabling other vehicle parameters to be determined (ie., speed, axle spacing, lane position, etc.). The averaging of the multiple load sensing device signals may be non-weighted, weighted, linear or non-linear, as appropriate or suitable.

In a preferred embodiment utilising a multiplicity of borehole load sensing devices the boreholes run perpendicular to the direction of traffic flow and are parallel to one another. In other embodiments, the boreholes are arranged at any other desirable angle to the traffic flow and parallel to one another. In yet other embodiments, the boreholes are each arranged at any desirable angle to the traffic flow and not necessarily parallel to one another (ie., Z pattern).

In a preferred embodiment of the invention, but without limitation, the borehole is constructed at a typical depth of between 500 to 1,000 mm below the pavement surface, which is usually into the sub-grade material of the road. In other embodiments, however, this depth can be shallower or deeper, as appropriate.

In preferred embodiments of the invention, but without limitation, the load sensing devices are installed in boreholes deep under the pavement. However, in other embodiments any suitable method for installing the load sensing devices deeply in the pavement may be utilised.

In a preferred embodiment of the invention, but without limitation, a load-sensing device operates across an entire lane of interest. However, in other embodiments the load sensing devices may operate partially across one or more lanes. In yet other embodiments, the load sensing devices may operate across a number of lanes.

In a preferred embodiment of the invention, but without limitation, the WIM sensing system utilises axle detectors as well as the load sensing devices. In other embodiments, the WIM system may not utilise axle detectors. In yet other embodiments, the WIM system may use a plurality of sensing and monitoring devices, such as load sensing devices, axle detectors, video surveillance

equipment, speed cameras, height detectors, remotely operated signage, visible alarms, audible alarms, electronic tag reading equipment, etc.

In a preferred embodiment of the invention, but without limitation, the axle detectors are co-directional and co-located with the load sensing devices, regardless of whether the axle detectors are installed on the surface of the road or in a borehole. In other embodiments of the invention, the axle detectors may be skewed.

In a preferred embodiment of the invention, but without limitation, the WIM system is a microprocessor based and fully automated instrument that can be monitored and controlled locally and/or remotely. Preferably, the system instrumentation comprises hardware and software components.

In a preferred embodiment of the invention, but without limitation, calibration of the site is performed on commissioning of a system and on periodic intervals, as deemed necessary by the authorities, the client or changing site conditions.

Preferably, but without limitation, the system provides velocity independent, static weight equivalent values for the vehicles that pass over the WIM site.

In a preferred embodiment of the invention, but without limitation, each borehole extrusion contains at least one load sensor and one axle detector. In some embodiments, a plurality of sensors may be used. In yet other embodiments a plurality of varying types of sensors may be utilised.

In preferred embodiments of the invention, but without limitation, the inventions disclosed in this provisional specification may be used for screening or enforcement WIM applications.

In preferred embodiments of the invention, but without limitation, the inventions disclosed in this provisional specification may be used for static, low-speed or high-speed WIM applications.

In a preferred embodiment, but without limitation, the sensors used for the construction of the load-sensing device are a series of eight electrical strain gauges or strain gauged strain amplifiers distributed across the length of the specially configured extrusion for a single lane width. An average or weighted average of the responses of the strain gauges is used to determine the load applied by a passing vehicle. With this arrangement it may also be possible to determine the wheel lane positions for a vehicle.. In other embodiments, a smaller or greater number of electrical strain gauges or strain gauged strain amplifiers are used. In yet other embodiments, point-sensitive fibre optic sensors are used in place of electrical strain gauges.

In a preferred embodiment of the invention, but without limitation, the axle detector is a conventional piezoelectric strip installed in the surface of the pavement. In another preferred embodiment, but without limitation, a novel linear modalmetric interferometer [33] is utilised as an axle detector inserted into saw-cuts on the surface of pavements or in the borehole extrusion. In other embodiments, any suitable sensing device, including piezoelectric strips, other fibre optic sensors, or the same strain gauge or fibre optic systems used in the load sensing devices, may be utilised for axle detection installed either in the surface of the pavement, embedded in the pavement or in a borehole extrusion under the pavement.

In a preferred embodiment, but without limitation, a single distributed fibre optic sensor is used for the construction of the load-sensing device across the length of the specially configured extrusion. In a preferred embodiment, the distributed fibre optic sensing technique is one of the two interferometric techniques disclosed further in this provisional specification. In a preferred embodiment, the fibre optic interferometer should have a sensor gauge length that is many multiples of the extrusion/lane length. With this capability, the fibre can be looped at the extreme ends of the desired sensing region of the extrusion so as to traverse the sensing region a multiple

number of times, thus increasing sensitivity a multiple number of times. Recent developments in the telecommunications industry of lower-cost solid state lasers with long coherence lengths now make it possible to extend the sensing length of interferometers, if configured correctly, to over 40 m. Previously, this would have required a relatively expensive, bulky and highly-stabilised gas laser, with demanding power requirements. The two interferometric techniques are further detailed below:

- Fibre Optic Michelson Interferometer

In the method, according to a preferred embodiment of the invention, highly coherent electromagnetic radiation at the appropriate sensing wavelength is launched into a singlemoded optical waveguide, such as an optical fibre, from a light source, such as a pigtailed DFB laser diode or fibre laser, preferably of a Bragg grating stabilised format, and propagates along the optical waveguide. Preferably a DFB laser diode with a coherence length of at least 60 metres is utilised. The optical waveguide is fusion spliced, or otherwise connected (temporarily or permanently), to one input arm of a singlemode optical waveguide isolator and when the electromagnetic radiation reaches the isolator the electromagnetic radiation can only propagate out into the output waveguide arm of the isolator. The electromagnetic radiation cannot propagate in the reverse direction through the isolator, thus optical reflections are stopped from possibly destabilising the DFB laser diode. The output waveguide arm of the isolator is then fusion spliced, or otherwise connected (temporarily or permanently), to one input arm of an optical waveguide light splitter or coupler (singlemoded) and when the electromagnetic radiation reaches the coupler the electromagnetic radiation can branch out into the output waveguide arms of the coupler. Thus, simultaneously, electromagnetic radiation is launched into the output waveguide arms of the coupler. The output arms of the coupler are fusion spliced, or otherwise connected (temporarily or permanently), directly to a reference arm and a sensing arm of the Michelson interferometer. Preferably, the sensing arm is longer than the reference arm. The sensing arm is then the part of the waveguide sensor that should be exposed to the sensing region of interest (ie., bonded to the specially configured extrusion). The two sensor arms are mirrored and the electromagnetic radiation signals are then recombined in the coupler to mix coherently and form a "fringe pattern" which is directly related to the optical phase difference experienced between the different optical beams (between the sensing arm and the reference arm). The fringe pattern optical signal is then branched out into two separate output arms of the coupler (in the opposite direction to the original light input). Electromagnetic radiation that propagates in the coupler arm towards the isolator and light source is attenuated by the isolator and prevented from being launched into the laser diode. The other output arm of the coupler is then terminated at an appropriate photodetector. Appropriate electronics, signal processing schemes and algorithms process the signals from the photodetector to obtain the desired information. Fringe counting (counting maxima or minima of the sensor output) can thus be performed in order to monitor any external parameters acting on the sensing arm.

- Fibre Optic Fabry-Perot Interferometer

The Fabry-Perot interferometer has the simplest configuration of all the fibre optic interferometers as it is essentially an optical cavity comprising of two mirror surfaces adjusted to be perfectly parallel to each other and perpendicular to the axis of the optical fibre. A change in the optical path length of the cavity, due to some external parameter, results in a phase retardance of the cavity modes. In the back-reflected configuration and low-Finesse cavities, the sensor output is very similar to that of the Michelson interferometer. Therefore to monitor any external parameters fringe counting (counting maxima or minima of the sensor output) can be performed.

Therefore, in the method, according to a second preferred embodiment of the invention, highly coherent electromagnetic radiation at the appropriate sensing wavelength is launched into a singlemoded optical waveguide, such as an optical fibre, from a light source, such as a pigtailed DFB laser diode or fibre laser, preferably of a Bragg grating stabilised format, and propagates along the optical waveguide. Preferably a DFB laser diode with a coherence length of at least 60 metres is utilised. The optical waveguide is fusion spliced, or otherwise connected (temporarily or permanently), to one input arm of a singlemode optical waveguide isolator and when the electromagnetic radiation reaches the isolator the electromagnetic radiation can only propagate out into the output waveguide arm of the isolator. The electromagnetic radiation cannot propagate in the reverse direction through the isolator, thus optical reflections are stopped from possibly destabilising the DFB laser diode. The output waveguide arm of the isolator is then fusion spliced, or otherwise connected (temporarily or permanently), to one input arm of an optical waveguide light splitter or coupler (singlemoded) and when the electromagnetic radiation reaches the coupler the electromagnetic radiation can branch out into the output waveguide arms of the coupler. One of the output waveguide arms of the coupler is unused and is fractured or otherwise terminated to avoid back-reflections. Thus, the electromagnetic radiation continues to propagate along only one of the output waveguide arms of the coupler. The output arm of the coupler is fusion spliced, or otherwise connected (temporarily or permanently), directly to the Fabry-Perot interferometer optical waveguide (singlemoded). The two mirrors of the interferometer are provided for by having a suitable Bragg grating at the start of the desired sensing region and the end of the optical waveguide is terminated with a mirror. The sensitive region of the sensing optical waveguide (between the grating and the end-mirror) is then the part of the waveguide sensor that should be exposed to the sensing region of interest (ie., bonded to the specially configured extrusion). Preferably, the interferometer is operated in a back-reflected configuration and designed to have a low-Finesse cavity. Thus, a change in the optical path length of the cavity (between the Bragg grating and the end-mirror), due to some external parameter, results in a phase retardance of the cavity modes and producing a response very similar to that of the Michelson interferometer (forming a "fringe pattern" which is directly related to the optical phase difference experienced between the different optical beams). The fringe pattern optical signal is then branched out into two separate output arms of the coupler (in the opposite direction to the original light input). Electromagnetic radiation that propagates in the coupler arm towards the isolator and light source is attenuated by the isolator and prevented from being launched into the laser diode. The other output arm of the coupler is then terminated at an appropriate photodetector. Appropriate electronics, signal processing schemes and algorithms process the signals from the photodetector to obtain the desired information.

The Fabry-Perot fibre optic sensor is extremely attractive as a fibre optic sensor due to it's single-fibre configuration, incorporating the lead-in, lead-out signals and common mode rejection into a single optical fibre, and due to its very high sensitivity with extremely good spatial and directional localisation characteristics.

All interferometers exhibit a sinusoidal or non-linear response to externally applied force. This non-linear relationship leads to a problem of signal fading and ambiguity in the direction of phase change (i.e. increasing or decreasing load). This problem can be solved by operating the sensor in its constant linear sensitivity range, otherwise known as the quadrature condition. The response signal is then processed through a signal processing system for phase demodulation and recovery. This is commonly known as quadrature phase demodulation.

Several techniques have been developed to achieve a linearisation of an interferometer's response. The passive homodyne technique is the most suitable for field applications and requires an interferometer configuration such that there are two output signals separated by a constant phase

difference of $\pi/2$ (90°). [34-38] One technique by which this is accomplished is by the use of a 3x3 six port [39-44] or 4x4 eight port [45-49] fibre directional coupler. The use of a 3x3 or 4x4 coupler produces, in general ($\pi/3$ for the 3x3) and exactly ($\pi/2$ for the 4x4), a sine and cosine signal:

$$\begin{aligned} I_1 &= A\,(1 + \sin\theta) \\ I_2 &= A\,(1 + \cos\theta) \end{aligned} \qquad (1)$$

where A is a constant factor and θ is the differential optical phase shift induced in the sensing region. These signals are detected by two photodetectors and processed to recover the phase.

Preferably the fibre optic interferometric sensors used in the WIM systems described in this provisional specification utilise passive quadrature phase demodulation to automate the fringe counting, resulting in an automated, unambiguous strain monitoring capability. In other embodiments other suitable phase demodulation or fringe counting techniques, such as active phase demodulation, are used.

Preferably, if a 3x3 or 4x4 coupler is used the unused arms are fractured or otherwise terminated to avoid back-reflections.

In a preferred embodiment of the invention, but without limitation, the silica waveguide is a singlemoded fibre at the sensing wavelength and the lead waveguides are singlemode fibres at the sensing wavelength.

In a preferred embodiment of the invention, but without limitation, all the optical fibres and fibre devices are connected by fusion splices. In other embodiments the optical fibres and fibre devices may be connected by any suitable or appropriate technique, such as mechanical splices, connectorised leads and through-adaptors, etc.

The effective sensing length of the waveguide sensor can be varied for either point or integrated sensitivity. Multi-point sensing can be achieved by quasi-distributed, distributed or multiplexed configurations.

Preferably the waveguide comprises at least one optical fibre and/or at least one optical fibre device. In some embodiments of the invention the waveguide may merely comprise an optical fibre without any additional sensing elements. However, the optical fibre can include sensing elements at its end or along its length and those sensing elements can comprise devices which will respond to a change in the desired parameter in the environment of application and influence the properties and characteristics of the electromagnetic radiation propagating in the waveguide to thereby provide an indication of the change in the parameter.

The waveguide or waveguides may be formed from any glass material, hard oxides, halides, crystals, sol-gel glass or polymeric material, or may be any form of monolithic substrate.

Preferably the detector means comprises:

- a photodetector for receiving the transmitted or reflected radiation from the sensing signal in the silica waveguide; and
- processing means for receiving signals from the photodetector and analysing the signals in order to register the sensed events.

Preferably any suitable CW or pulsed single or multiple wavelength source or plurality of sources may be employed. In a preferred embodiment, without limitation, a CW or pulsed high coherence DFB laser diode is utilised to supply the optical signal. In an alternate arrangement, multiple light sources, of the same or varying wavelengths, may be used to generate the sensing signal or a

Preferred embodiments of the present invention offer the potential to utilise all-fibre, low-cost optical devices in conjunction with laser diodes, photodetectors, isolators, couplers, WDM couplers and filters.

In preferred embodiments of the present invention any suitable light source, coupler and photodetector arrangement may be used with the sensor systems. In a preferred embodiment, the required optical properties of the light source are such that the sensor gauge length is many multiples of the extrusion/lane length. With this capability, the fibre can be looped at the extreme ends of the desired sensing region of the extrusion so as to traverse the sensing region a multiple number of times, thus increasing sensitivity a multiple number of times.

In preferred embodiments of the present invention, without limitation, lead-in and lead-out fibre desensitisation and sensor localisation is achieved. In other embodiments it may be possible to have lead-in or lead-out sensitivity or no sensor localisation.

Preferably, but without limitation, utilisation of properties and characteristics of the electromagnetic radiation propagating in the waveguide sensor enables monitoring to take place in a non-destructive manner. Thus, the sensor is not necessarily damaged, fractured or destroyed in order to monitor and locate the desired parameter.

A preferred method for mirroring the optical fibre end-face involves placing the fibre in a vacuum system and the prepared fibre end-face is then coated with a metallic material such as Au, Ag, Al or Ti or a dielectric material such as TiO_2. This coating can be prepared by using thermal evaporation, electron beam evaporation or sputtering. Other coating or mirroring materials and techniques may also be utilised.

In preferred embodiments of the present invention, without limitation, the manufactured sensor and/or the exposed fusion spliced region may be protected by encapsulating or coating the desired region in fusion splice protectors or any suitable material (ie. ultraviolet acrylate, epoxy, etc.).

Preferably the instrument optical and electronic arrangements will utilise noise minimisation techniques.

Preferably, all the optical and electrical components will be located in a single instrument control box, with individual optical fibre input/output ports.

Optical devices, electro-optic devices, acousto-optic devices, magneto-optic devices and/or integrated optical devices may also be utilised in the system.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments of the present invention will be further illustrated, by way of example, with reference to the following drawings in which:

Figure 1 is a view showing a general embodiment of the load sensing device of the present invention, utilising the U-channel extrusion;

Figure 2 is a photograph showing a general embodiment of the of the load sensing device of the present invention for the completed U-channel extrusion;

Figure 3 is a view showing a general embodiment of the load sensing device of the invention for the flat beam inserted into a conduit extrusion;

Figure 4 is a photograph showing a general embodiment of the of the load sensing device of the present invention for the completed flat beam inserted into a conduit extrusion;

Figure 5 is a view showing a general embodiment of the invention for a configuration of electrical strain gauges or strain gauged strain amplifiers attached to the extrusion;

Figure 6 is a view showing a general embodiment of the invention for a configuration of a single length of fibre optic sensor attached to the extrusion;

Figure 7 is a view showing a general embodiment of the invention for a configuration of a fibre optic sensor gauge length that is many multiples of the extrusion/lane length attached to the extrusion, such that the fibre is looped at the extreme ends of the desired sensing region of the extrusion so as to traverse the sensing region a multiple number of times, thus increasing sensitivity a multiple number of times;

Figure 8 is a view showing a general embodiment of the invention for the borehole configuration from a cross-sectional top view;

Figure 9 is a view showing a general embodiment of the invention for the borehole configuration from a cross-sectional side view and utilising a surface attached axle detector;

Figure 10 is a view showing a general embodiment of the invention for the borehole configuration from a cross-sectional side view and utilising a borehole installed axle detector;

Figure 11 is a view showing a general embodiment of the invention for the borehole configuration from a cross-sectional trench-end view;

Figure 12 is a set of photographs showing the method of preparing the borehole according to the description given in Figure 11.

Figure 13 is a view showing a general embodiment of the invention for the fibre optic Michelson interferometer;

Figure 14 is a view showing a general embodiment of the invention for the fibre optic Michelson interferometer utilising a passive homodyne demodulation configuration;

Figure 15 is a view showing a general embodiment of the invention for the fibre optic Fabry-Perot interferometer;

Figure 16 is a view showing a general embodiment of the invention for the fibre optic linear modalmetric interferometer [33] utilised as an axle detector;

Figure 17 is a view showing a general embodiment of the invention for a complete WIM system utilising load sensing devices in two instrumented boreholes;

Figure 18 is a view showing the real-time monitoring screen from the WIM system display; and

Figure 19 is a view showing the response of the fibre optic linear modalmetric interferometer [33] utilised as an axle detector.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Preferred embodiments of the invention, without imposing any limitations, will be further described with reference to the above mentioned drawings. The drawings and the following embodiments are provided in as general a form as possible to avoid confusion. While it may not be specifically stated or illustrated in the following embodiments and drawings, in the preferred embodiments the following features are utilised, and not intentionally omitted, where appropriate:

- suitable electrical and/or optical devices are employed at one or both ends of the system to detect and process the signals;
- utilisation of properties and characteristics of the electromagnetic radiation propagating in the waveguide sensor enables monitoring to take place in a non-destructive manner. Thus, the

sensor is not necessarily damaged, fractured or destroyed in order to monitor the desired parameter;

- utilisation of all-fibre, low-cost optical devices in conjunction with laser diodes, photodetectors, couplers, WDM couplers, isolators and filters;
- the wavelength couplers are 2x2 3dB couplers, in other embodiments they may be any suitable multi-port device, such as 2x1, 3x1, 3x3, 4x4, etc.; and
- the optical fibres and fibre devices are connected by fusion splices. In other embodiments the optical fibres and fibre devices are connected by any suitable or appropriate technique, such as mechanical splices, connectorised leads and through-adaptors, etc.

Figure 1 illustrates the U-channel extrusion **2** utilised in a general embodiment of the load sensing device **50** of the present invention.

Figure 2 shows a photograph for the completed U-channel extrusion **2** according to a general embodiment of the load sensing device **50** of the present invention.

Figure 3 illustrates the flat beam **4** inserted into a conduit extrusion **6** utilised in a general embodiment of the load sensing device **50** of the present invention.

Figure 4 shows a photograph for the completed flat beam **4** inserted into a conduit extrusion **6** according to a general embodiment of the of the load sensing device **50** of the present invention.

Figure 5 is a view showing a general embodiment of the invention for a configuration of electrical strain gauges or strain gauged strain amplifiers **12** attached to the inner flat surface of the U-channel **2** or the flat beam **4**.

Figure 6 is a view showing a general embodiment of the invention for a configuration of a single length of fibre optic sensor **22** attached to the inner flat surface of the U-channel **2** or the flat beam **4**.

Figure 7 is a view showing a general embodiment of the invention for a configuration of a fibre optic sensor gauge length that is many multiples of the extrusion/lane length **24** attached to the inner flat surface of the U-channel **2** or the flat beam **4**, such that the fibre is looped **26** at the extreme ends of the desired sensing region of the extrusion so as to traverse the sensing region a multiple number of times, thus increasing sensitivity a multiple number of times.

Figure 8 is a view showing a general embodiment of the invention for the borehole configuration from a cross-sectional top view. With reference to Figure 8, according to a preferred embodiment of the present invention, a suitable diameter, horizontal borehole **34** is made across the pavement **30** lane **32** of interest using any suitable boring technique. Following installation of the load measuring device **50** and axle detector **52/56** into the borehole **34**, the site of borehole entry **38** is restored to its original form, rendering the site invisible to vehicles.

Figure 9 is a view showing a general embodiment of the invention for the borehole configuration from a cross-sectional side view and utilising a surface attached axle detector. With reference to Figure 9, according to a preferred embodiment of the present invention, a suitable diameter, horizontal borehole **34** is made across the pavement **30** lane **32** of interest using any suitable boring technique. The borehole **34** is constructed at a typical depth of between 500 to 1,000 mm below the pavement **30** surface, which is usually into the sub-grade material **36** of the road. A load measuring device **50** is inserted in the borehole **34** operating along the entire length of the device so as to cover the lane **32** of interest. After inserting the load measuring device **50**, the remaining borehole void **35** is filled with an epoxy filler. An axle detector **52** is mounted on the surface of the pavement **30** as closely co-directional and co-located with the instrumented borehole **34** as possible in order to provide certain information. The load measuring device **50**

sensor leads **54** are protected in a suitable manner where they exit the borehole **34** and run in conduits **59** to the WIM system instrumentation **40**. Likewise, the axle detector **52** leads **53** are protected in a suitable manner where they exit the pavement **30** and run in conduits **59** to the WIM system instrumentation **40**. Finally, the site of borehole entry **38** is restored to its original form, rendering the site invisible to vehicles.

Figure 10 is a view showing a general embodiment of the invention for the borehole configuration from a cross-sectional side view and utilising a borehole installed axle detector. With reference to Figure 10, according to a preferred embodiment of the present invention, a suitable diameter, horizontal borehole **34** is made across the pavement **30** lane **32** of interest using any suitable boring technique. The borehole **34** is constructed at a typical depth of between 500 to 1,000 mm below the pavement **30** surface, which is usually into the sub-grade material **36** of the road. A load measuring device **50** is inserted in the borehole **34** operating along the entire length of the device so as to cover the lane **32** of interest. After inserting the load measuring device **50**, the remaining borehole void **35** is filled with an epoxy filler. An axle detector **56** is also mounted in the borehole load measuring extrusion **50** in order to provide certain information. The load measuring device **50** sensor leads **54** and the axle detector **56** leads **57** are protected in a suitable manner where they exit the borehole **34** and run in conduits **59** to the WIM system instrumentation **40**. Finally, the site of borehole entry **38** is restored to its original form, rendering the site invisible to vehicles.

Figure 11 is a view showing a general embodiment of the invention for the borehole configuration from a cross-sectional trench-end view. With reference to Figure 11, according to a preferred embodiment of the present invention, a trench **38** is dug beside the road for the boring equipment to gain access to the appropriate depth under the pavement **30** for the construction of the WIM borehole **34**. A suitable diameter, horizontal borehole **34** is made across the pavement **30** lane **32** of interest using any suitable boring technique. The borehole **34** is constructed at a typical depth of between 500 to 1,000 mm below the pavement **30** surface, which is usually into the sub-grade material **36** of the road. Following installation of the load measuring device **50** and axle detector **52/56** into the borehole **34**, the site of borehole entry **38** is restored to its original form, rendering the site invisible to vehicles.

Figure 12 shows a set of photographs for the method of preparing the borehole according to the description given in Figure 11.

Figure 13 is a view showing a general embodiment of the invention for the fibre optic Michelson interferometer utilised to instrument the load measuring device. With reference to Figure 13, according to a preferred embodiment of the present invention, CW coherent laser light is launched into a singlemode optical fibre **15**, from a pigtailed DFB laser diode **60** and fibre isolator **62**, and propagates along the optical fibre **15**. Preferably, a DFB laser diode with a coherence length of at least 60 metres is utilised. The optical fibre **15** is terminated at a singlemode fibre optic bulkhead connector (through adaptor) **64a**. A jacketed, connectorised singlemode fibre lead **16a** is connected to the through adaptor **64a**, such that the light from the optical fibre **15** is launched into the fibre lead **16a**. The optical fibre lead **16a** is fusion spliced **66** to one arm **68** of a singlemode 2x2, 3 dB fibre optic coupler **70** and when the light reaches the coupler **70** the light can branch out into the two output arms **72** and **78** of the coupler **70**. Thus, coherent laser light is simultaneously launched into the two output arms **72** and **78** of the coupler **70**. The two output arms **72** and **78** of the coupler **70** are fusion spliced **74** and **80** directly to a reference arm **12** and a sensing arm **10** of the Michelson interferometer. The reference arm **12** is made as short as practicable (around 100 mm). The sensing arm **10** is then the part of the fibre sensor that should be bonded to the sensing region of the specially configured extrusion **2** or **4**. The fibre sensing arm **10** length should be made many multiples of the extrusion/lane length **24** such that the fibre **10** is looped **26** at the extreme ends of the desired sensing region of the extrusion **2** or **4** so as to traverse the

sensing region a multiple number of times, thus increasing sensitivity a multiple number of times. The reference **12** and sensing **10** arms are mirrored **76a** and **76b** and the laser light signals are then reflected back to recombine in the coupler **70** to mix coherently and form a "fringe pattern" which is directly related to the optical phase difference experienced between the different optical beams (between the sensing arm **10** and the reference arm **12**). The fringe pattern optical signal is then branched out into two separate output arms **68** and **82** of the coupler **70**, in the opposite direction to the original light input. The optical signal in coupler arm **68** propagates towards the isolator **62** and DFB laser diode **60** and is attenuated by the isolator **62** and prevented from being launched into the laser diode **60**. The optical signal in coupler output arm **82** propagates through fibre splice **84** and along a jacketed, connectorised singlemode fibre lead **16b** to a singlemode fibre optic bulkhead connector (through adaptor) **64b**. This optical signal is then launched into an optical fibre **17** that is terminated at an appropriate photodetector **86**. Appropriate electronics, signal processing schemes and algorithms process the signals from the photodetector **86** to obtain the desired information. Fringe counting (counting maxima or minima of the sensor output) can thus be performed in order to monitor any external parameters acting on the sensing arm **10**. For practical field implementation and obtaining total sensor lead insensitivity, all items within the box marked **2/4** are incorporated in the extrusion **2** or **4**. All items within the box marked **20** are incorporated in the load sensing device instrumentation **20** of the WIM system instrumentation **40**. Additionally, the insensitive fibre optic leads **16a** and **16b** may be made sufficiently long as to allow the load sensing device **50** to be remotely located from the load sensing device instrumentation **20**. The insensitive fibre optic leads **16a** and **16b** will normally run in a conduit **59** to the load sensing device instrumentation **20**.

Figure 14 is a view showing a general embodiment of the invention for the fibre optic Michelson interferometer utilising a passive homodyne demodulation configuration. With reference to Figure 14, according to another preferred embodiment of the present invention, CW coherent laser light is launched into a singlemode optical fibre **15**, from a pigtailed DFB laser diode **60** and fibre isolator **62**, and propagates along the optical fibre **15**. Preferably, a DFB laser diode with a coherence length of at least 60 metres is utilised. The optical fibre **15** is terminated at a singlemode fibre optic bulkhead connector (through adaptor) **64a**. A jacketed, connectorised singlemode fibre lead **16a** is connected to the through adaptor **64a**, such that the light from the optical fibre **15** is launched into the fibre lead **16a**. The optical fibre lead **16a** is fusion spliced **66** to one arm **68** of a singlemode 3x3 unitary fibre optic coupler **88** and when the light reaches the coupler **88** the light can branch out into the three output arms **72, 78** and **79** of the coupler **88**. Thus, coherent laser light is simultaneously launched into the three output arms **72, 78** and **79** of the coupler **88**. One output arm **79** of the coupler **88** is fractured or otherwise terminated **89** to avoid back-reflections. The remaining two output arms **72** and **78** of the coupler **88** are fusion spliced **74** and **80** directly to a reference arm **16** and a sensing arm **14** of the Michelson interferometer. The reference arm **16** is made as short as practicable (around 100 mm). The sensing arm **14** is then the part of the fibre sensor that should be bonded to the sensing region of the specially configured extrusion **2** or **4**. The fibre sensing arm **14** length should be made many multiples of the extrusion/lane length **24** such that the fibre **14** is looped **26** at the extreme ends of the desired sensing region of the extrusion **2** or **4** so as to traverse the sensing region a multiple number of times, thus increasing sensitivity a multiple number of times. The reference **16** and sensing **14** arms are mirrored **76a** and **76b** and the laser light signals are then reflected back to recombine in the coupler **88** to mix coherently and form a "fringe pattern" which is directly related to the optical phase difference experienced between the different optical beams (between the sensing arm **14** and the reference arm **16**). The fringe pattern optical signal is then branched out into the three separate output arms **68, 82b** and **82c** of the coupler **88**, in the opposite direction to the original light input. The optical signal in coupler arm **68** propagates towards the isolator **62** and DFB laser diode **60** and is attenuated by the isolator **62** and prevented from being launched

into the laser diode **60**. The optical signals in coupler output arms **82b** and **82c** propagate through fibre splices **84b** and **84c** and along jacketed, connectorised singlemode fibre leads **16b** and **16c** to singlemode fibre optic bulkhead connectors (through adaptors) **64b** and **64c**. These optical signals are then launched into optical fibres **17b** and **17c,** which are terminated at appropriate photodetectors **86b** and **86c**. Appropriate electronics, signal processing schemes and algorithms process the signals from the photodetector **86b** and **86c** to obtain the desired information. Automated fringe tracking (strain monitoring) can thus be performed using suitable quadrature phase demodulation algorithms in order to monitor any external parameters acting on the sensing arm **14**. For practical field implementation and obtaining total sensor lead insensitivity, all items within the box marked **2/4** are incorporated in the extrusion **2** or **4**. All items within the box marked **20** are incorporated in the load sensing device instrumentation **20** of the WIM system instrumentation **40**. Additionally, the insensitive fibre optic leads **16a, 16b** and **16c** may be made sufficiently long as to allow the load sensing device **50** to be remotely located from the load sensing device instrumentation **20.** The insensitive fibre optic leads **16a, 16b** and **16c** will normally run in a conduit **59** to the load sensing device instrumentation **20.**

Figure 15 is a view showing a general embodiment of the invention for the fibre optic Fabry-Perot interferometer. With reference to Figure 15, according to a further preferred embodiment of the invention, CW coherent laser light is launched into a singlemode optical fibre **15**, from a pigtailed DFB laser diode **60** and fibre isolator **62**, and propagates along the optical fibre **15**. Preferably, a DFB laser diode with a coherence length of at least 60 metres is utilised. The optical fibre **15** is then fusion spliced **90** to one input arm **92** of a singlemode 2x2, 3 dB fibre optic coupler **70** and when the light reaches the coupler **70** the light can branch out into the two output arms **72** and **78** of the coupler **70**. The output arm **78** of the coupler **70** is unused and is fractured or otherwise terminated **89** to avoid back-reflections. Thus, the coherent laser light continues to propagate along only one of the output arms **72** of the coupler **70**. The output arm **72** of the coupler **70** is then terminated at a singlemode fibre optic bulkhead connector (through adaptor) **64**. A jacketed, connectorised singlemode fibre lead **16** is connected to the through adaptor **64,** such that the light from the output arm **72** of the coupler **70** is launched into the fibre lead **16**. The optical fibre lead **16** is fusion spliced **94** directly to the singlemode sensing arm **18** of the Fabry-Perot interferometer. The two mirrors of the interferometer are provided for by having a suitable Bragg grating **96** at the start of the desired sensing region and the end of the sensing fibre **18** is terminated with a mirror **76**. The sensitive region of the sensing fibre **18** (between the Bragg grating **96** and the end-mirror **76**) is then the part of the fibre sensor that should be bonded to the sensing region of the specially configured extrusion **2** or **4**. The fibre sensing arm **18** length should be made many multiples of the extrusion/lane length **24** such that the fibre **18** is looped **26** at the extreme ends of the desired sensing region of the extrusion **2** or **4** so as to traverse the sensing region a multiple number of times, thus increasing sensitivity a multiple number of times. In this configuration, the interferometer is operated in a back-reflected configuration and designed to have a low-Finesse cavity. Thus, a change in the optical path length of the cavity (between the Bragg grating **96** and the end-mirror **76**), due to an applied load, results in a phase retardance of the cavity modes and produces a response very similar to that of the Michelson interferometer (forming a "fringe pattern" which is directly related to the optical phase difference experienced between the different optical beams). Thus, the fringe pattern optical signal is then reflected back through fibre lead **16** and through adaptor **64,** into the input arm **72** of the coupler **70** and branched out into two separate output arms **92** and **98** of the coupler **70**, in the opposite direction to the original light input. The optical signal in coupler arm **92** propagates towards the isolator **62** and DFB laser diode **60** and is attenuated by the isolator **62** and prevented from being launched into the laser diode **60**. The optical signal in coupler output arm **98** propagates through fibre splice **99,** into an appropriate optical fibre terminated photodetector **86**. Appropriate electronics, signal processing schemes and algorithms process the signals from the photodetector **86** to obtain the

desired information. Fringe counting (counting maxima or minima of the sensor output) can thus be performed in order to monitor any external parameters acting on the sensing arm **18**. For practical field implementation and obtaining total sensor lead insensitivity, all items within the box marked **2/4** are incorporated in the extrusion **2** or **4**. All items within the box marked **20** are incorporated in the load sensing device instrumentation **20** of the WIM system instrumentation **40**. Additionally, the insensitive fibre optic lead **16** may be made sufficiently long as to allow the load sensing device **50** to be remotely located from the load sensing device instrumentation **20**. The insensitive fibre optic leads **16** will normally run in a conduit **59** to the load sensing device instrumentation **20**.

Figure 16 is a view showing a general embodiment of the invention for the fibre optic linear modalmetric interferometer [33] utilised as an axle detector. With reference to Figure 16, according to a preferred embodiment of the invention, a fibre optic modalmetric sensor **110** comprises a multimode fibre **118** which is mirrored on it's end-face **115** and fusion spliced **117** to a singlemode fibre patch cord **116**. The free end of the fibre optic modalmetric sensor **110** is attached or bonded to the sensing region of the specially configured extrusion **2** or **4**. The singlemode fibre patch cord **116** is coupled to instrumentation **120**, which includes a light source **122**, coupler **126** and a photodetector **124** and signal processing unit **42**. The output arm **132** of the coupler **126** is unused and is fractured or otherwise terminated **128** to avoid back-reflections. Thus, the laser light continues to propagate along only one of the output arms **134** of the coupler **126**. The output arm **134** of the coupler **126** is then terminated at a singlemode fibre optic bulkhead connector (through adaptor) **130**. A jacketed, connectorised singlemode fibre lead **116** is connected to the through adaptor **130**, such that the light from the output arm **134** of the coupler **126** is launched into the fibre lead **116**. The light source **122** provides light which is propagated along the singlemode fibre **114** in the singlemode fibre patch cord **116** and, which in the embodiment of figure 16, is reflected back along the optical fibres **110** and **116** for detection by the photodetector **124**. However, in other embodiments the detecting unit **124** could be located at the end of the optical fibre **110** and the laser light could merely be detected by the unit **124** without the need for reflection. The propagated light in the multimode fibre **118**, which is eventually detected by the detector unit **124**, has its properties and characteristics altered by a change in the load or strain experience by the sensing fibre **118**. Figure 19 illustrates the response for a 1-2-3 axle vehicle driving over a borehole-installed axle detector using this method.

Figure 17 is a view showing a general embodiment of the invention for a complete WIM system utilising load measuring devices in two instrumented boreholes. Figure 17 is a general embodiment in which any of the electrical strain gauge or fibre optic sensors methods described above may be used in the load measuring device **50**, axle detectors **52/56** may be either surface or borehole installed and axle detectors **52/56** may be any suitable sensing device, including piezoelectric strips, the fibre optic linear modalmetric interferometer [33] described in Figure 16, or the same strain gauge or fibre optic systems used in the load measuring device **50**.

With reference to Figure 17, according to a preferred embodiment of the present invention, a pair of suitable diameter, horizontal boreholes **34** are made across the pavement **30** lane **32** of interest using any suitable boring technique. The boreholes **34** are constructed at a typical depth of between 500 to 1,000 mm below the pavement **30** surface, which is usually into the sub-grade material of the road. A load measuring device **50** is inserted into each of the boreholes **34** operating along the entire length of the device so as to cover the lane **32** of interest. After inserting the load measuring devices **50**, the remaining borehole voids are filled with an epoxy filler. Axle detectors **52/56** are also mounted either on the pavement **30** surface or in the borehole load measuring extrusions **50** in order to provide certain information. The load measuring devices **50** sensor leads **54** and the axle detectors **52/56** leads **53/57** are protected in a suitable manner where they exit the boreholes **34** and run in one or more conduits **59** to the WIM system

instrumentation **40**. The site of borehole entry is restored to its original form, rendering the site invisible to vehicles. The sensor leads **54** and **53/57** terminate in their respective sensing device instrumentation **20** housed in an instrumentation rack **42**, where all the appropriate electronics, signal processing schemes and algorithms process the signals from the various sensors. The sensor information is then transferred to the WIM system PC **44**, which analyses, records, displays and transmits the final information to the system operator. In some embodiments, the WIM system PC **44** is not located locally, but it is communicated to remotely by the WIM system instrumentation **40**.

Figure 18 is a view showing the real-time monitoring screen, from the WIM system display, of results obtained during field trials.

Figure 19 is a view showing the response of the fibre optic linear modalmetric interferometer [33] utilised as an axle detector for a six axle (1-2-3 configuration) vehicle driving over a borehole-installed sensor.

The methodologies and systems disclosed in this provisional specification were developed under a four-year R&D project supported by the Australian Government Department of AusIndustry, through the Industry Innovation Program Competitive Grants scheme. The title of that project was: "Fibre Optic Weigh-In-Motion Detection in the Infrastructure Field", AusIndustry Project Ref. No. GRA00175. This was a collaborative project involving Future Fibre Technologies Pty. Ltd. (FFT), ARRB Transport Research Ltd. (ARRB) and Remedial Engineering Pty. Ltd. (RE).

Preferred embodiments of the invention have been successfully developed and tested as illustrated by the following description of the outcomes of the collaborative R&D Project. The sensors were constructed in order to determine the feasibility of producing a suitably sensitive electrical strain gauge system and fibre optic interferometric sensors with relatively long sensing lengths. Not all of the results obtained to date are detailed in the following summary.

The following table summarises the technical achievements of the project, and the current state of the various technologies and products.

Technology	Future	Comments
Below-Pavement Borehole technique for installation of WIM sensors. Named the: Stealth WIM System	The Stealth WIM System has been confirmed to be unique by patent attorneys. FFT and ARRB are working on jointly filing an international patent application.	Following much investigation, this technique was found to be highly effective. Represents a fundamental shift in the installation of WIM sensors, and proven to have excellent operational and commercial potential. **Recommendation:** Long-term performance testing remains to fully validate the ultimate accuracy of this system. This is currently taking place at 3 independent sites.
Fibre Optic Linear Modalmetric Interferometer [33]	Only suitable as a WIM screening sensor requiring <±15% error on GVM. Effective as a vehicle axle detector.	Large variation in results (±15%). Good results obtained when used as an axle detector. **Recommendation:** To use this type of sensor for axle detection applications only.

Fibre Optic Fabry-Perot Interferometer	Shows good promise for enforcement quality device requiring <±5% error on GVM.	FFT was successful in developing a new configuration for this sensor that increased the output of the device by a factor of 10. Using a light calibration vehicle, this type of sensing technique has achieved an overall error of ±4% for 95% of vehicles measured. We believe this error consisted largely of vehicle suspension oscillations caused by road surface roughness and wind effects. **Recommendation:** Tests have shown that this sensing technology demonstrates considerable promise as a WIM sensor.
Fibre Optic Michelson Interferometer	Shows good promise for enforcement quality device requiring <±5% error on GVM.	FFT was successful in developing a new configuration for this sensor that increased the output of the device by a factor of 10. Using a light calibration vehicle, this sensing technique has achieved an overall error of ±3.6% for 95% of vehicles measured. We believe this error consisted largely of vehicle suspension oscillations caused by road surface roughness and wind effects. **Recommendation:** Tests have shown that this sensing technology demonstrates considerable promise as a WIM sensor.
Electrical strain gauge (ESG) Stealth WIM System	System is currently aimed at satisfying ASTM 1813 Type 1 accuracy, achieving ±10% GVM accuracy for 95% of vehicles measured.	Following much investigation, this technique was found to be highly effective. Represents a fundamental shift in the installation of WIM sensors, and proven to have excellent operational and commercial potential. **Recommendation:** Long-term performance testing remains to fully validate the ultimate accuracy of this system. This is currently taking place at 2 independent sites.
WIM System Data Logger	Commercial availability imminent.	A new and dedicated hardware data logging system for the Stealth WIM System. The logging system hardware consists of several electronic card modules housed in an enclosure. The system continuously monitors the WIM sensors and stores information for each axle traversing the sensors. The information can be used in 'real-time' or down loaded at a later date for post processing. **Recommendation:** The logging system continues to perform well. Minor changes will be made to the prototype before full production commences.
Link System And WIM Link Enforcement Module	Commercial availability imminent.	This is the Stealth WIM System software and manual. The Stealth Enforcement (Enforce) system has been produced to enable the monitoring and screening of vehicle masses, without the need to stop each vehicle. The Stealth WIM System software uses the project WIM technologies to display and record the mass, speed and classification of vehicles at highway speeds. **Recommendation:** The Enforce software has been built using object oriented technology to allow similar applications to be built more easily by using the same code base.

The electrical strain gauge and fibre optic based WIM systems were fully tested in the laboratory and then experimentally verified for their effectiveness as WIM sensors at several field

installations in Melbourne, Australia. As seen in the summary table above, the experimentally verified accuracies were very good. FFT and ARRB are now conducting long-term field trials of the systems to determine their ultimate reliability and accuracy. The uncertainties of ±4% achieved for the fibre optic systems were obtained with a single sensor embedded in the pavement. Using multiple, parallel sensors should assist to decrease the uncertainty by averaging-out wind, speed and rough pavement effects on vehicle suspensions, as well as enabling other vehicle parameters to be determined (ie., speed, axle spacing, lane position, etc.).

It should also be emphasised that the uncertainty of ±4% was achieved for a light vehicle (5 tons), which is more prone to wind, speed and rough pavement effects than heavy vehicles. In previous tests, the fibre optic systems achieved an error of around ±6.8% using a calibration vehicle unloaded and fully loaded over a total of 18 passes. When removing some anomalous results from the 18 passes and examining the loaded passes only, a figure of ±1.2% was achieved. When examining the unloaded passes only, a figure of ±5.6% error was achieved, indicating that vehicle dynamics were contributing significant error when the vehicle was unloaded.

An important feature of WIM systems is the incorporation of axle detectors. Traditionally, piezoelectric strips are attached to the surface or cut into the surface of a pavement. This requires traffic to be stopped for installation and is visible. Consequently, the fibre optic linear modalmetric interferometer [33] was incorporated into the same borehole extrusions as the fibre optic load measuring sensors and successfully tested as an axle detector. A typical response for a 6-axle (1-2-3) truck is shown in Figure 19.

Significant progress was also made in developing the final electronic hardware and software design for a cost-effective field system. The results have been summarised in the summary table above. The data logger consists of several electronic cards housed in an enclosure. Several WIM sensor inputs are provided, as well as axle detector inputs. The data logger matches up axle detections with strains produced by an axle travelling over the WIM sensor/s and stores this information, along with the date/time, into the data logger's internal memory. The information is also available in 'real-time' to allow the system to be used as part of an enforcement screening system. A modem is usually connected to the system to provide remote data down loading capability or monitoring. The Enforce software has been assembled using object oriented technology. The basic building blocks now exist so that other similar applications can be produced relatively quickly, using a proven code base. The Enforce software allows local or remote monitoring of vehicles travelling over the WIM sensors. For each vehicle typical parameters are displayed in real-time. In addition, many violation checks are performed on each vehicle. A typical view of the main screen is show in Figure 18.

APPLICATIONS OF THE PREFERRED EMBODIMENTS

The development of a flexibly-sited, enforcement quality WIM system based on the inventions disclosed in this provisional application should open a new market segment with worldwide application and commercialisation potential. Many road authorities are seeking this type of equipment by trialing existing technologies, however, the very high accuracy and reliability demanded at highway speeds for enforcement, and the need for ease of installation, have thwarted these attempts. Market research, to date, indicates that the method and systems disclosed in this provisional specification offer the world's first practical, commercially viable, enforcement quality WIM systems.

Direct discussions with the industry have verified that there is very good commercial potential for the disclosed inventions, if the systems are cost effective, easy to install, do not require a culvert, do not require road closures, are at least as accurate as CULWAY, have low power consumption,

are easy to use and invisible to road users. This is a lot to ask for in a WIM system, but achievable with the inventions disclosed in this provisional specification.

It is important to note that the technology is considered to have good potential over competing techniques particularly because of the simplicity of sensor installation into the pavement, the excellent potential for system automation (ie., using cameras and remote communications) and reduction in the required installation and operational infrastructure costs.

Not inclusively, but indicatively, the following examples illustrates some applications in which a system according to the present invention may be used:

- Static Weighing of Vehicles, such as cars, trucks, rail, aircraft, etc.
- Weigh-in-Motion of Vehicles, such as cars, trucks, rail, aircraft, etc.
- High Accuracy Weigh-in-Motion
- Low Accuracy Weigh-in-Motion
- High Speed Weigh-in-Motion
- Low Speed Weigh-in-Motion
- Weighing of Objects other than Vehicles
- Conveyer Weighing of Goods
- Weighing of People and/or Pedestrians
- Weighing of Livestock
- Potential clients for the disclosed WIM systems include:
    - Road Authorities
    - Transport Firms and Operators
    - Private Road Ventures
    - Toll-Road Operators/Owners
    - Rail Authorities and Freight Operators
    - Airport Authorities
    - Law Enforcement Authorities
    - Security Firms
    - Defence Authorities
    - Government Agencies
    - Instrument Manufacturers and Distributors
    - Systems Manufacturers and Distributors
    - Systems Integrators, Manufacturers and Distributors

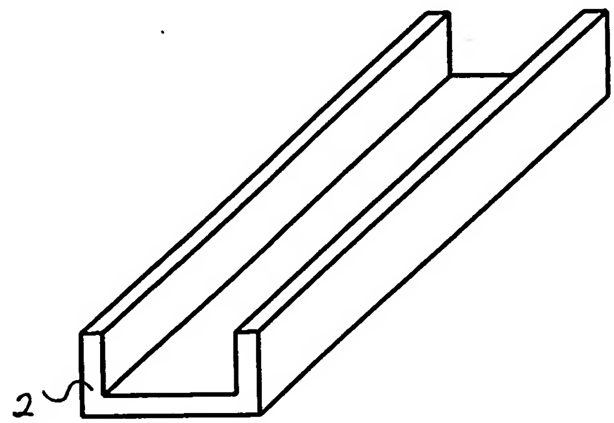
Since modifications within the spirit and scope of the invention may readily be effected by persons skilled within the art, it is to be understood that this invention is not limited to the particular embodiments described by way of example hereinabove.

FUTURE FIBRE TECHNOLOGIES PTY. LTD. and
ARRB TRANSPORT RESEARCH LTD.

By EDWARD TAPANES, Director of FFT Pty. Ltd.
(Name of Applicant)
(BLOCK LETTERS)

11 October 1999
(Date)

Figure 1



U-Channel Extrusion

Figure 2

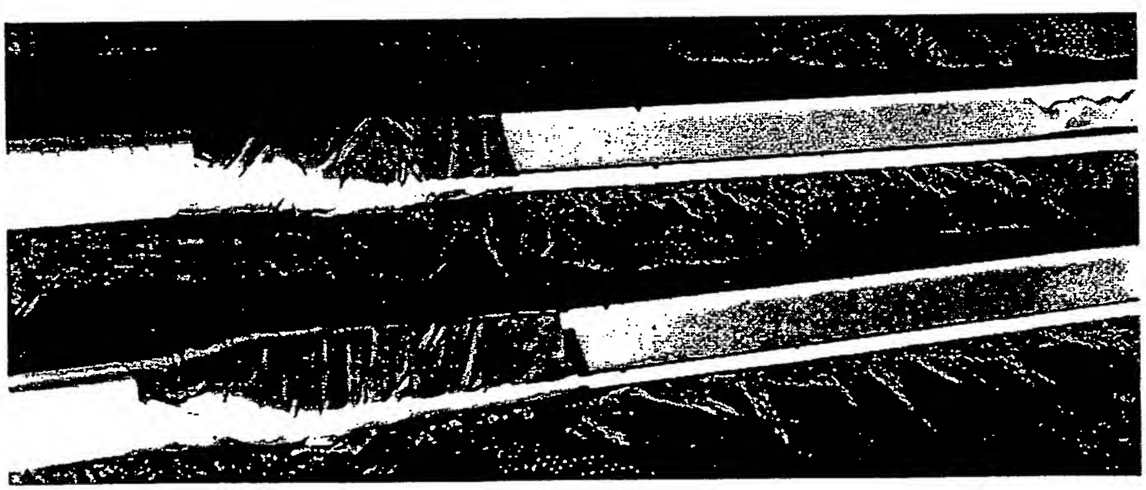
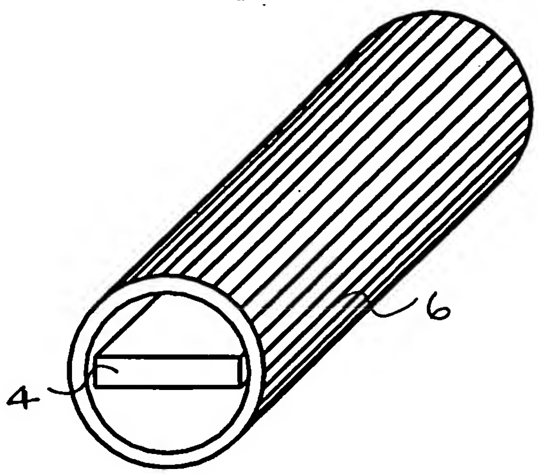


Figure 3



Circular conduit extrusion with sensors attached to inner extrusion

Figure 4

Figure 5

Strain Gauge Extrusion

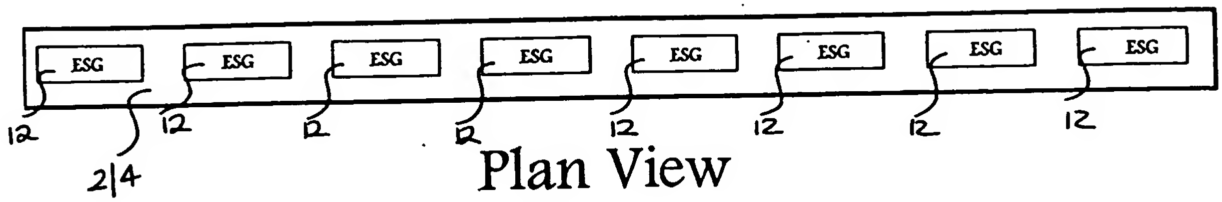


Figure 6

Fibre Optic Extrusion

Plan View - Single fibre run

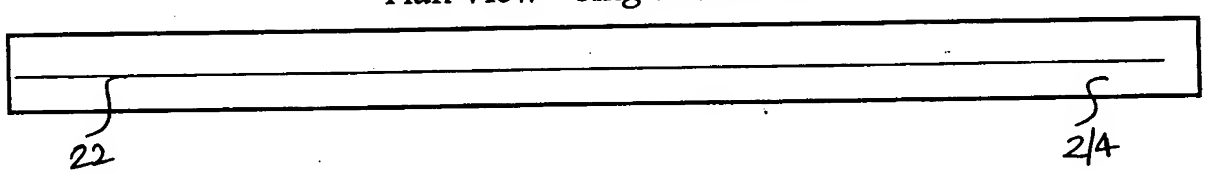


Figure 7

Fibre Optic Extrusion

Plan View - Multiple fibre loop

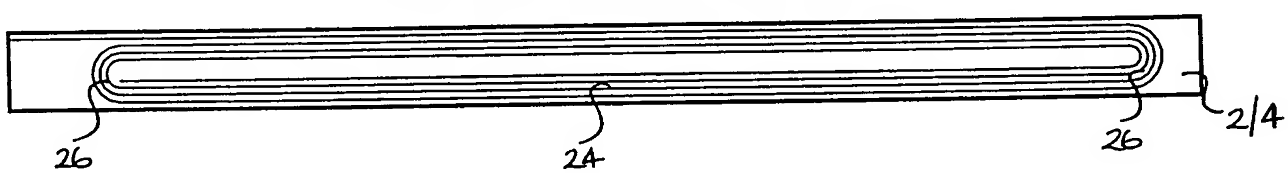


Figure 8

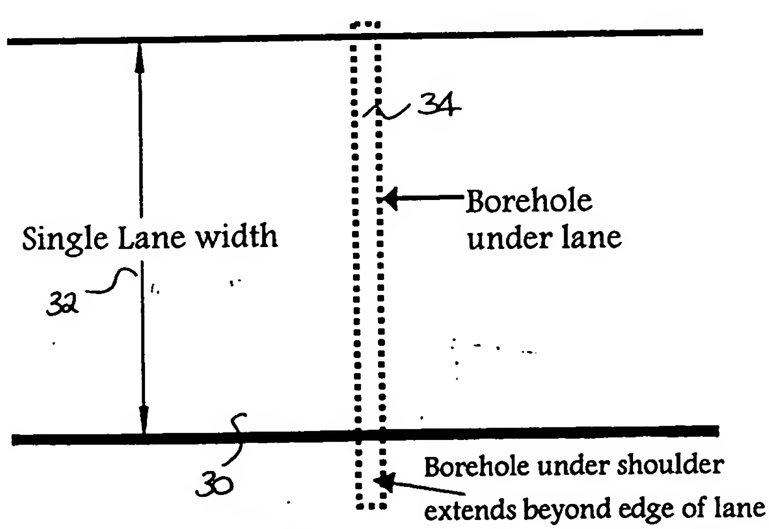


Figure 9

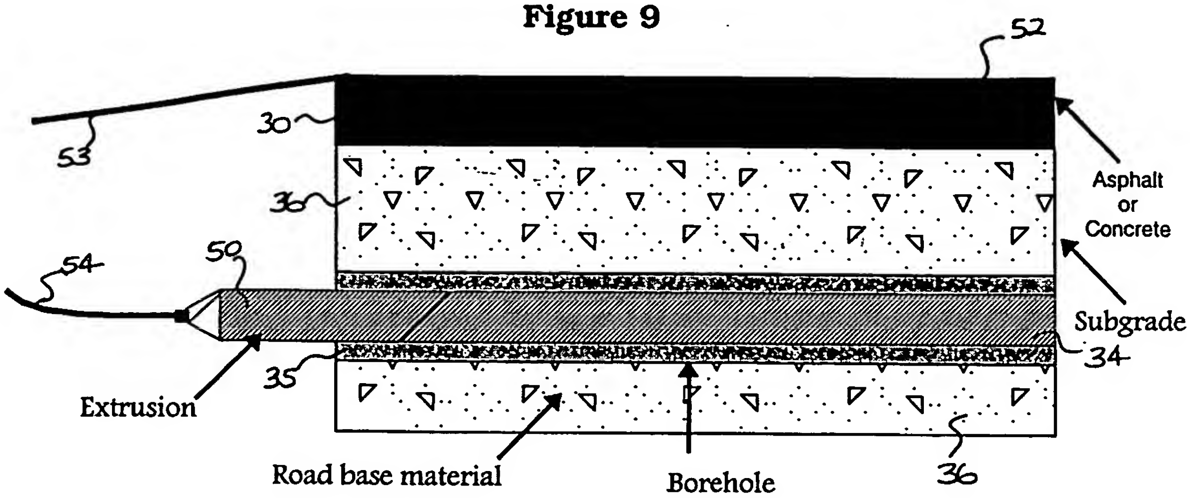


Figure 10

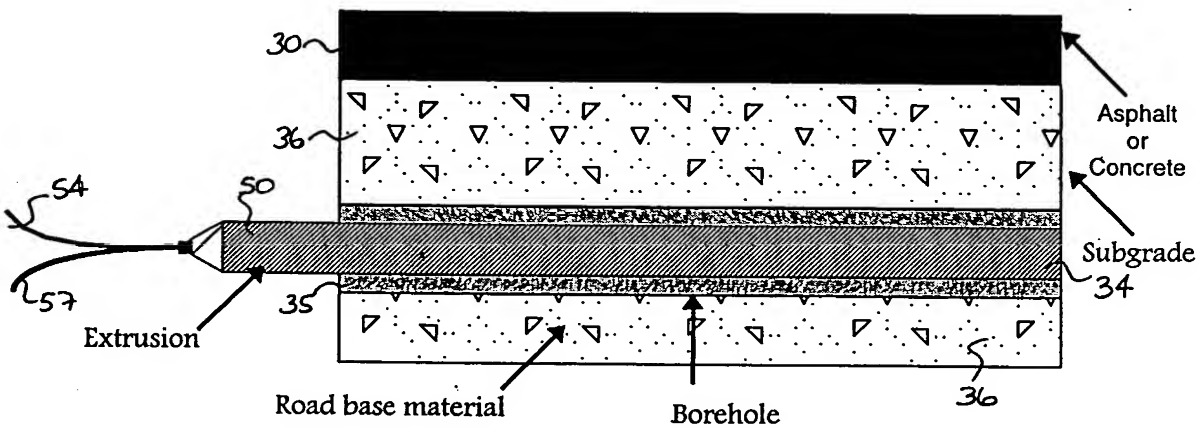


Figure 11

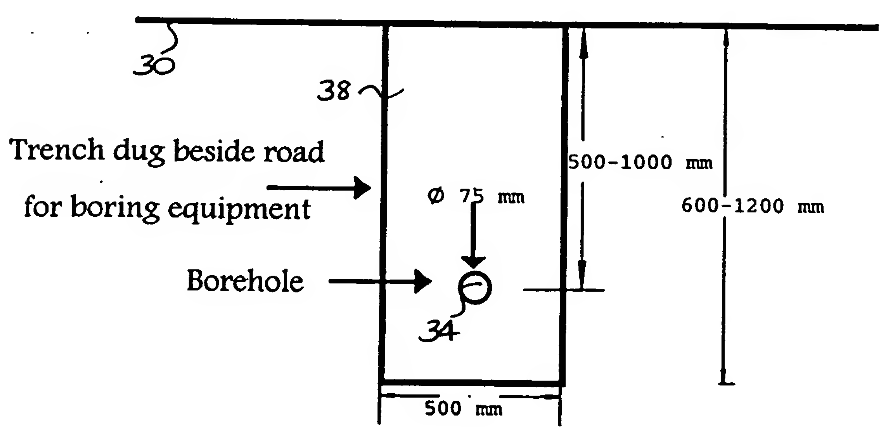


Figure 12

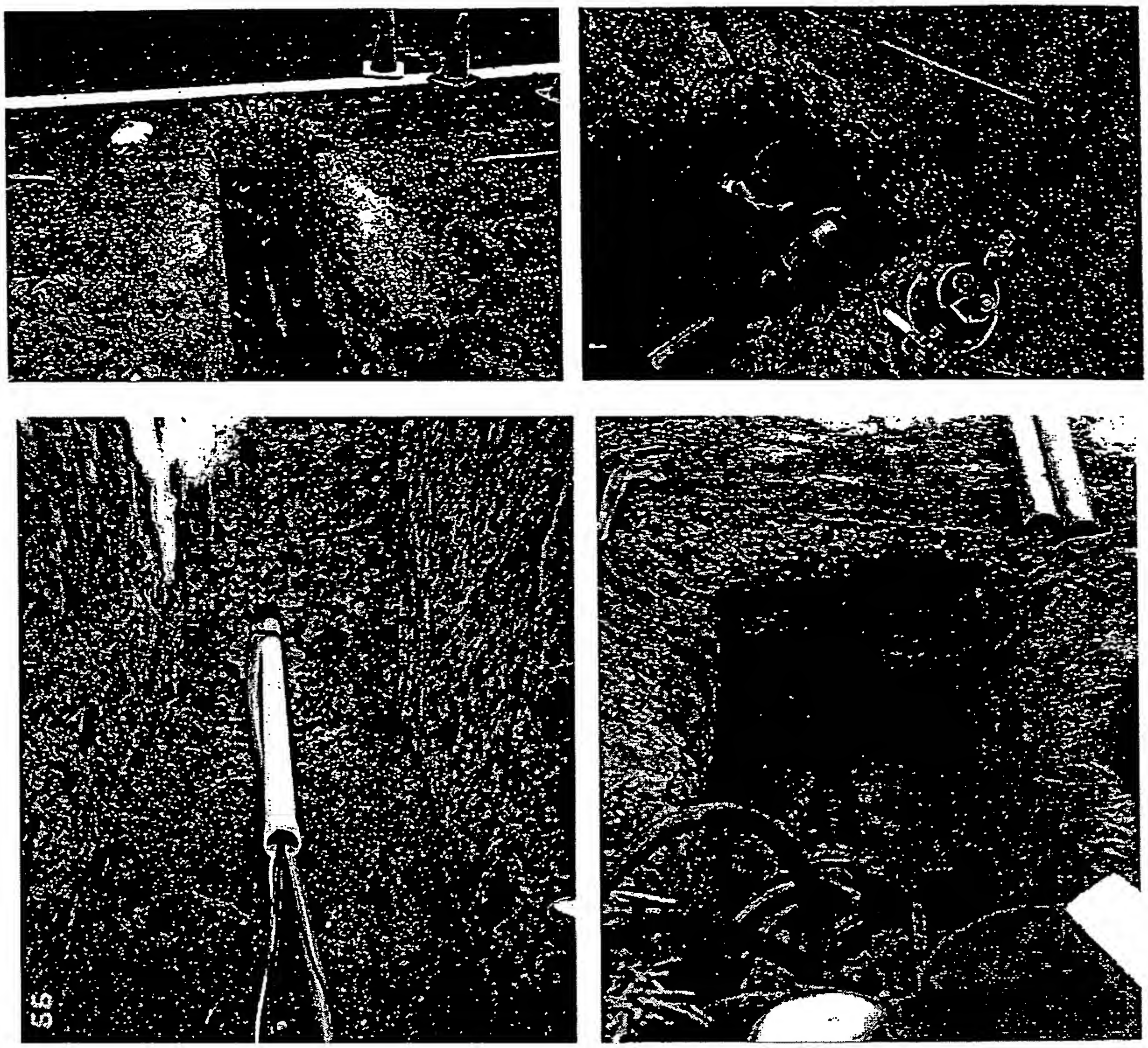


Figure 13

Typical Michelson Interferometer arrangement

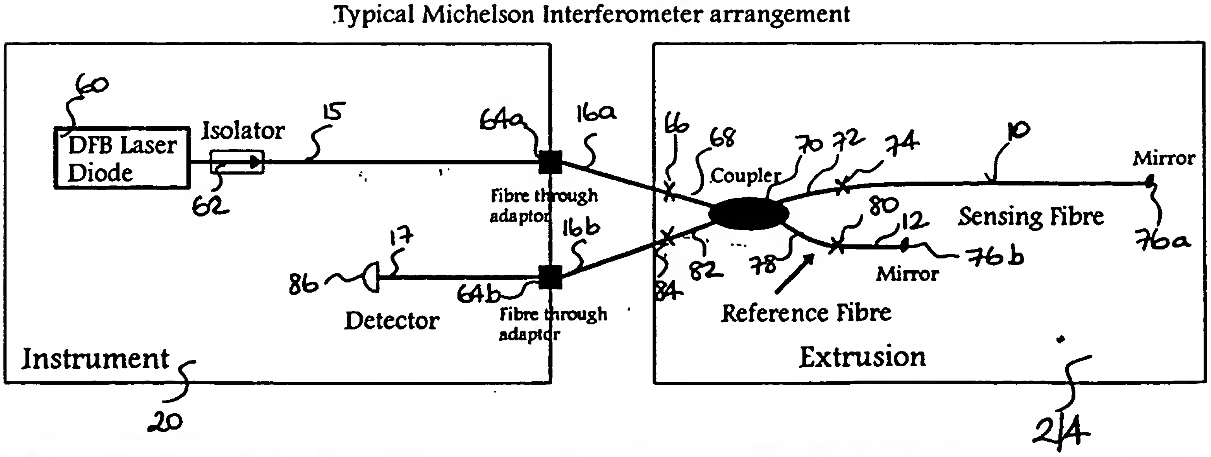


Figure 14

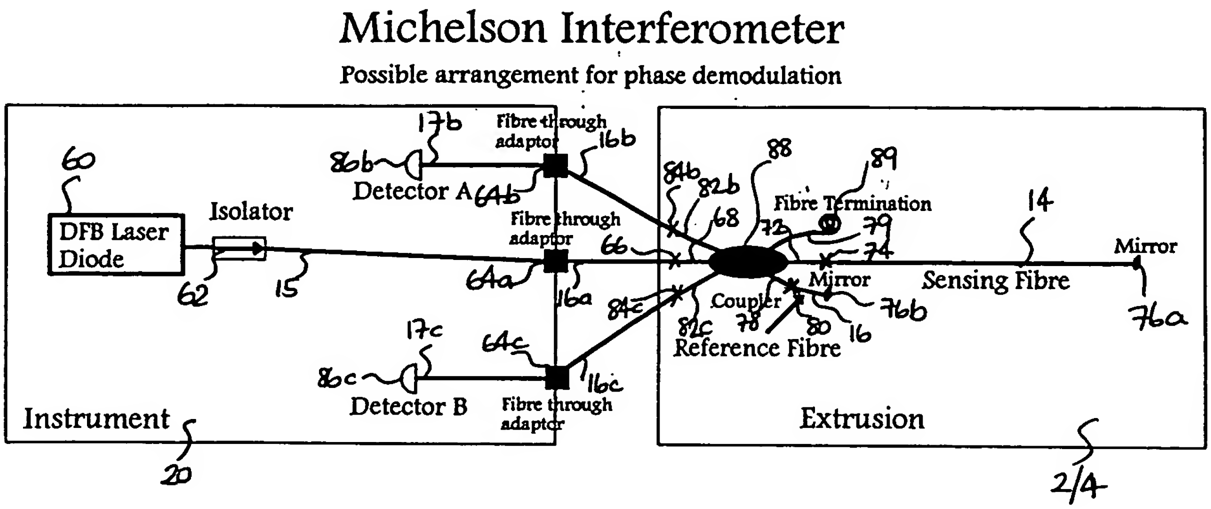


Figure 15

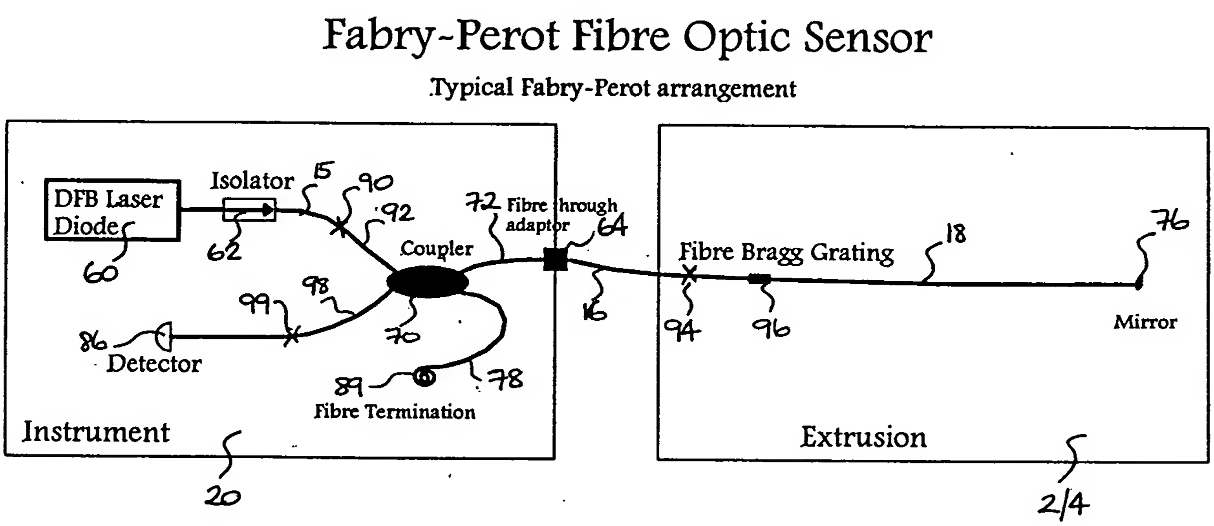


Figure 16

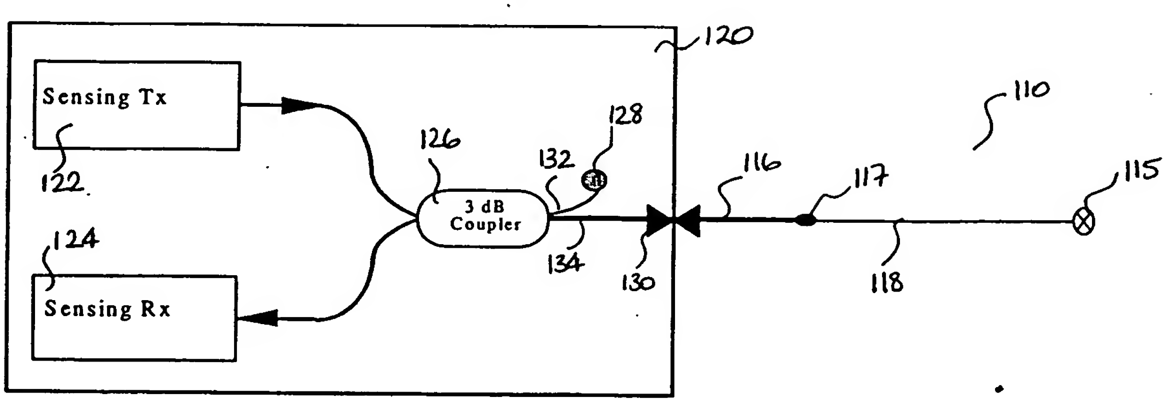
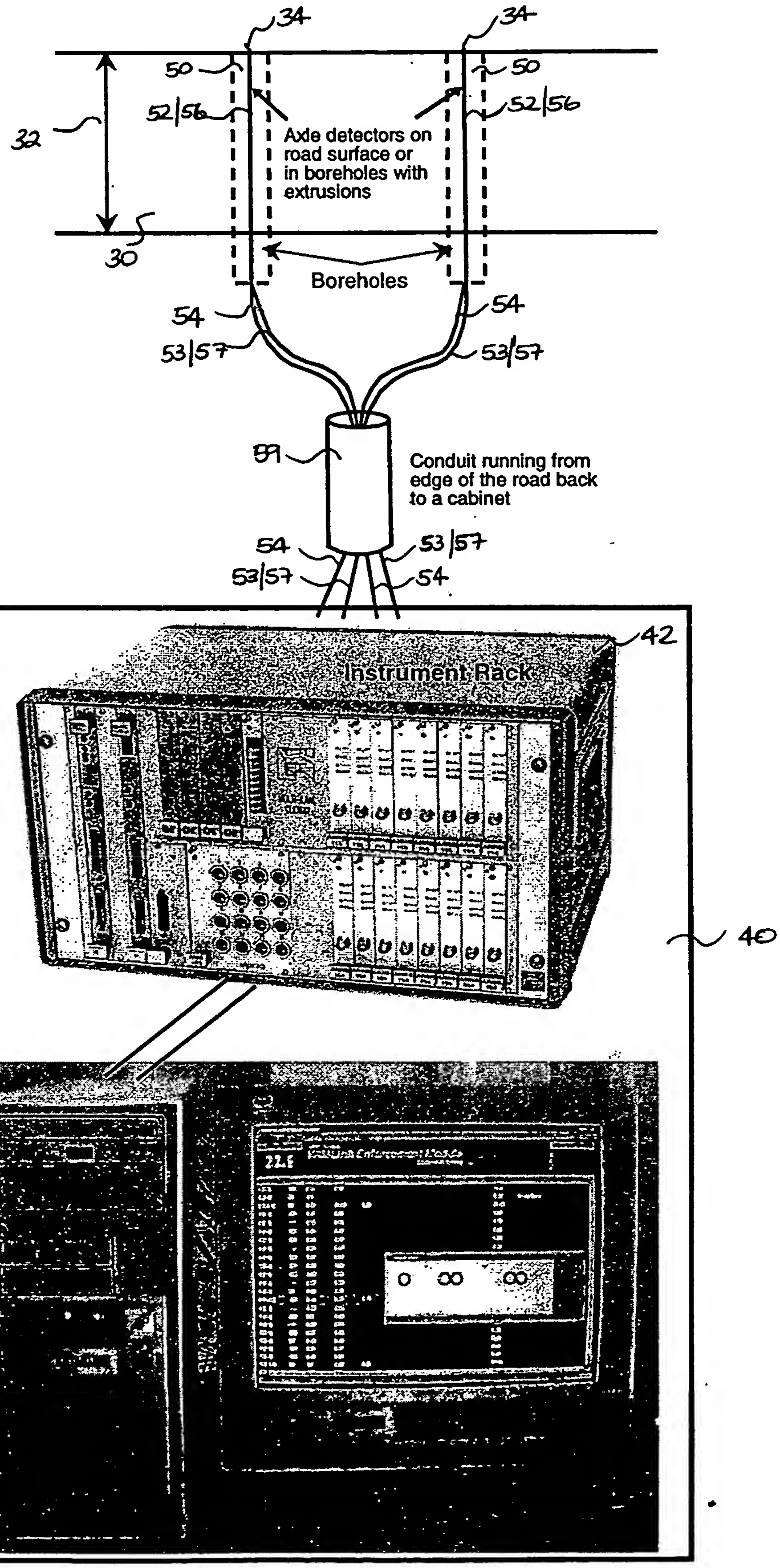


Figure 17


34
34
50
50
52|56
52|56
32
Axle detectors on road surface or in boreholes with extrusions
30
Boreholes
54
54
53|57
53|57
59
Conduit running from edge of the road back to a cabinet
54
53|57
53|57
54
42
Instrument Rack
40
44

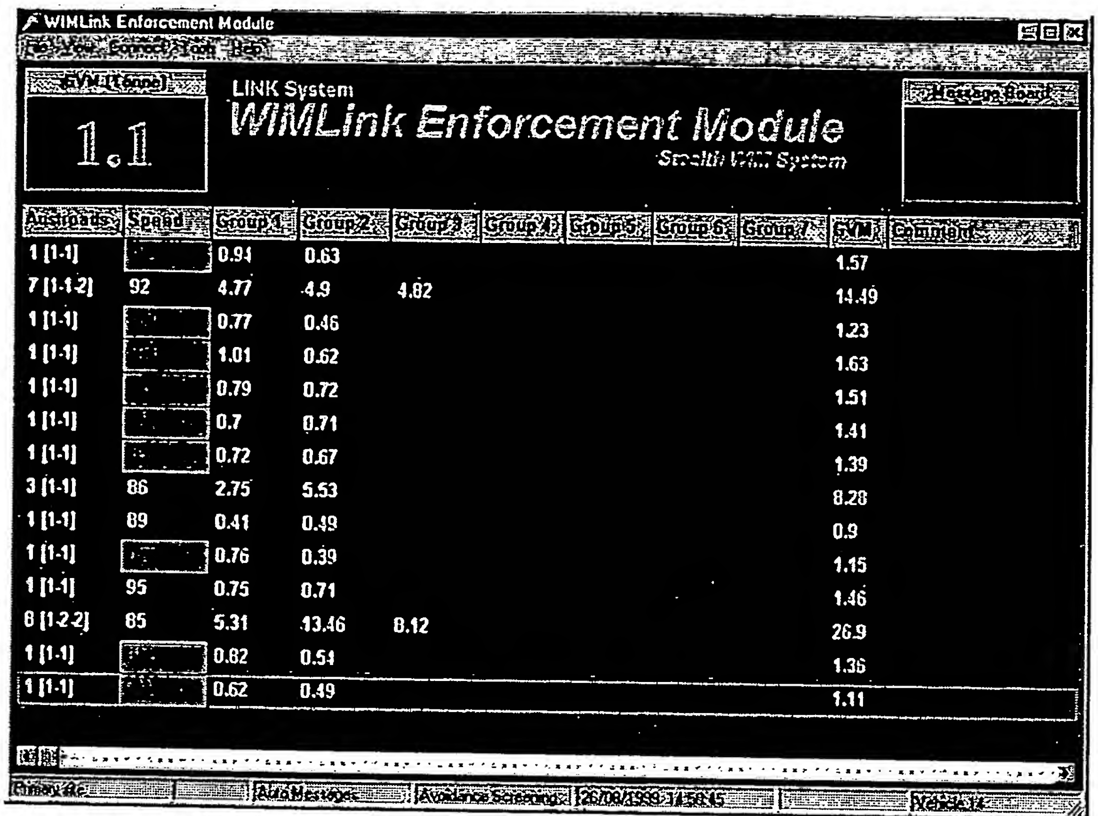


Figure 18

Figure 19